Understanding the Diffusion of Energy Efficiency Technology in Residential Buildings

by

Eric Russell Martin

S.B. Civil and Environmental Engineering
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Signature of Author ....
Department of Civil and Environmental Engineering
18 July, 1997

Certified by ....
Fred Moavenzadeh
George Macomber Professor of Construction Management
Director, Technology and Development Program
Thesis Supervisor

Accepted by ....
Richard de Neufville
Chairman, Technology and Policy Program

Accepted by ....
Joseph M. Sussman
Chairman, Departmental Committee on Graduate Studies

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ABSTRACT

New concerns, in particular the mitigation of climate change and the staggering unrealized energy efficiency potential in residential buildings, have prompted new interest in improving energy efficiency. This thesis, using an inductive approach, characterizes the dynamic of energy efficiency technology diffusion in residential buildings by examining the forces that drive and hinder diffusion. The thesis also evaluates the effect of federal regulation of household appliances on technological innovation and technology diffusion.

A case study approach, applying management of technology models of the diffusion process, is used to analyse the diffusion of passive solar systems. A regulatory analysis is performed on the *National Appliance Energy Conservation Act of 1987*.

It is found that, among other factors, the configurational, design-based nature of passive solar technology hinders its diffusion. This effect is likely to apply to a majority of important building energy efficiency technologies. At the same time, the federal regulation of building energy efficiency, particularly appliance energy efficiency, is found to be weak and ineffective in taking advantage of current technology levels.

Finally, the thesis outlines how a technology-based strategy to improve residential energy efficiency can be created.

Thesis Advisor:	Fred Moavenzadeh.
Titles:	George Macomber Professor of Construction Management; Director, Technology and Development Program.

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Background

INTRODUCTION

Energy efficiency in buildings was a popular topic in the late 1970s and the early 1980s. It then fell out of favour. New concerns have prompted renewed interest in the topic, and they demand a new approach. I propose one that is technology-based.

Researching issues in energy efficiency by studying individual technologies sheds new light on some of the determinants of efficiency. If technology-based measures are eventually implemented, they are not easily reversed, like many behavioral changes. Technology-based measures are also likely to be politically more palatable than, for example, fuel price increases. Furthermore, there are aspects of technological change that have gone unrecognized by the conventional regulatory paradigm. In this thesis I aim to demonstrate how a technology approach can be used to understand energy efficiency and also how a technology-based strategy to improve energy efficiency might be framed.

Nathan Rosenberg, an economics professor at Stanford University, offers the following view on our use of technology:

> In retrospect, it is apparent that we have persistently underestimated the contribution of technological change to the growth of the economy. As part of the same bias, we have failed to anticipate the same contribution that

> technological change would make to alleviating or eliminating certain future problems that earlier generations regarded as both serious and intractable. (Rosenberg, 1986).

Although in my opinion Rosenberg is enamoured of unlimited technological development to the point of over-optimism, he does capture one essential element of technology: its ability to improve the performance of certain systems along several dimensions simultaneously, safety and cost, for example. This has important consequences. A standard economic "balancing" of costs and benefits is often an incorrect framing of the problem because the potential of technology has not been properly taken into account. Ashford, Ayers, and Stone (1985) summarize the traditional economic problem as follows:

> Environmental, health, and safety regulation, as seen by economists, should correct market imperfections by internalizing the social costs of industrial production. Regulation results in a redistribution of the costs and benefits of industrial activity among manufacturers, employers, workers, consumers, and other citizens. Within the traditional economic paradigm, economically efficient solutions reflecting the proper *balance* between costs and benefits of given activities are the major concern.

Economists view technology as the relationship between the inputs and outputs of a production process. This view does not highlight the ability of technology to improve a system along two or more dimensions simultaneously. Ashford, Ayers and Stone's description of a *technology-based* approach to regulation is instructive:

> Underlying a regulatory strategy based on the assessment of technological options is a rejection of the premise that regulation must achieve a *balance* between environmental integrity and industrial growth, or between job safety and competition in world markets. Rather, such a strategy builds on the thesis that health, safety, and environmental goals can be *co-optimized* with economic growth through technological innovation.

Once this characteristic of technology is ascertained, it remains for us to harness its power to improve energy efficiency. We must differentiate analytical and prescriptive stages of the exercise. Once the action of technology in the building sector is properly analyzed, an effective policy can be designed. The focus of this thesis is on analysis.

I look at representative examples of energy efficiency technology diffusion and regulation to determine the causes of sub-optimal efficiency. I then make some general inferences about the technological dynamic of the sector.

1.1 Motivations for Research

There are three motivations for this research: a growing concern for the value-based notion of sustainability; mitigating the risk of emissions-induced climate change, and the extraordinary costs savings potential associated with improved energy efficiency. Each is discussed in turn.

A. Sustainability

The concept of sustainability is of growing interest to economists, political scientists and others. The general idea is that development should "meet the needs of the present without compromising the ability of future generations to meet their own needs" (Bruntland Report, in Pezzey, 1989). However, this is a broad definition only, and there is no consensus on an operationalized definition of the concept.

Given this general goal, what can be done to encourage sustainability or sustainable development? Proposals to implement some form of sustainability include such items as "transfers from developed to developing countries, transfers from present to future generations, national accounting methods more sensitive to the state of the environment, project valuation methods that place greater emphasis on environmental assets" (Liddle, 1996), and resource and product prices that internalize various associated negative environmental externalities.

I focus on the "no regrets" option. This type of action is consistent with the general notion of sustainability but because it is also cost-effective, justified on the basis of economics alone. Elaboration on "no regrets" energy efficiency options for the building sector is provided in subsection C.

B. Climate Change

Climate change has become "a staple of national and international politics" (Skolnikoff, 1990). It is a complicated, uncertain problem with potentially terrible consequences. As in the case of sustainability, "no regrets" options are easy to justify. Here, the state of the problem is described; there are interrelated science and policy dimensions.

Current scientific understanding of climate change is straightforward. There exists a record of the earth's climate over the last 250 thousand years, reconstructed from, among other things, core samples from Antarctica ice caps. The earth's temperature has been increasing at a rate more rapid than any change in the last 10 thousand years. This increase has been associated with an increase in the atmospheric concentrations of carbon dioxide (from fossil fuel combustion), methane (from decay in municipal dumps, rice growing, cattle raising), and other greenhouse gasses. These gasses absorb short-wave radiation from the sun and reradiate it as heat. This effect is not disputed in the scientific community. The scientific uncertainty surrounds the likely response of the global climate system to the measured increase in greenhouse gasses, and that proportion of recent temperature change that can be attributed to human activity. Attempts to prognosticate system response take the form of sophisticated climate models. However, these suffer from inherent limits to predictability[1] and a general lack of accuracy. For example, state-of-the-art models currently embody localized corrections of up to one half the solar input (Prinn, 1997).

Some of the potential consequences of rapid warming are increased drought and desertification, more pronounced weather extremes, "sea level rise by one-third to one-half meter by the middle of next century," and "possibly serious nonlinear effects as shifts of major ocean currents" due to extremely rapid ecosystem change (Skolnikoff, 1990). In summary, it can be deduced from the science of the problem that we are faced with a potentially very serious consequences and that there is a great deal of uncertainty surrounding the magnitude, likelihood, and timing of these consequences.

According to Skolnikoff (1990), the essence of the policy problem is that "outside the security sector, policy processes confronting issues with substantial uncertainty do not normally yield policy that has high economic or political costs." "Indeed, no major action is likely to be taken until those uncertainties are substantially reduced, and probably not before evidence of warming and its effects are actually visible. Unfortunately, any increase in temperature will be irreversible by the time the danger becomes obvious enough to permit political action." What can be done to mitigate the risk of pronounced and irreversible climate change? While not absolving ourselves of the collective responsibility to address this issue comprehensively, a logical place to start is with "no regrets" options. These options would simultaneously act to mitigate greenhouse gas emissions and avoid unnecessary energy expenditures. They are, as explored in the next subsection, largely justified on the basis of economics alone.

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[1]For example, because of its nature as a chaotic system, it is not possible to initialize an ocean circulation model with enough precision to have it provide meaningful output in the long term.

C. *"No Regrets" Mitigation Options*

A definitive work on "no regrets" climate change mitigation options is that of Rubin et. al., 1992. In this paper, the authors built a supply curve showing the "marginal cost of an incremental reduction in CO_2-equivalent emissions from introducing a new mitigation measure" (Rubin et. al., 1992). The resulting curve is reproduced in Figure 1. Building sector improvements figure prominently in the results. In fact, they realize a profit of between 50 and 75 dollars per avoided ton of CO_2-equivalent. Figure 2 shows the structure of electricity-related building sector mitigation "supply" in finer detail.

Although these savings are modest from the point of view of an individual household, the aggregated potential energy savings are staggering. The relative lack of importance of these measures at the household level may partially explain their lack of diffusion. A systematic explanation of the reasons for this inefficiency, however, does not exist. Hirst and Brown (1990) cite structural barriers ("distortions in fuel prices, uncertainty about future fuel prices, limited access to capital, government fiscal and regulatory policies, codes and standards, and supply infrastructure limitations") and behavioural barriers ("attitudes towards energy efficiency, perceived risk of energy-efficiency investments, information gaps, and misplaced incentives"). Some of these effects do indeed seem credible, but the magnitude of their effect is very difficult to ascertain or verify: energy use depends on a complex and interrelated set of variables, and it is impossible to conduct an experiment to test their respective effects. Clearly it is desirable to realize some or all of these efficiency gains. This thesis applies models of technological innovation and innovation diffusion, proved to be reliable in other circumstances, in order to gain a better understanding of unrealized efficiency in the residential building sector. Using these business economics models frames and

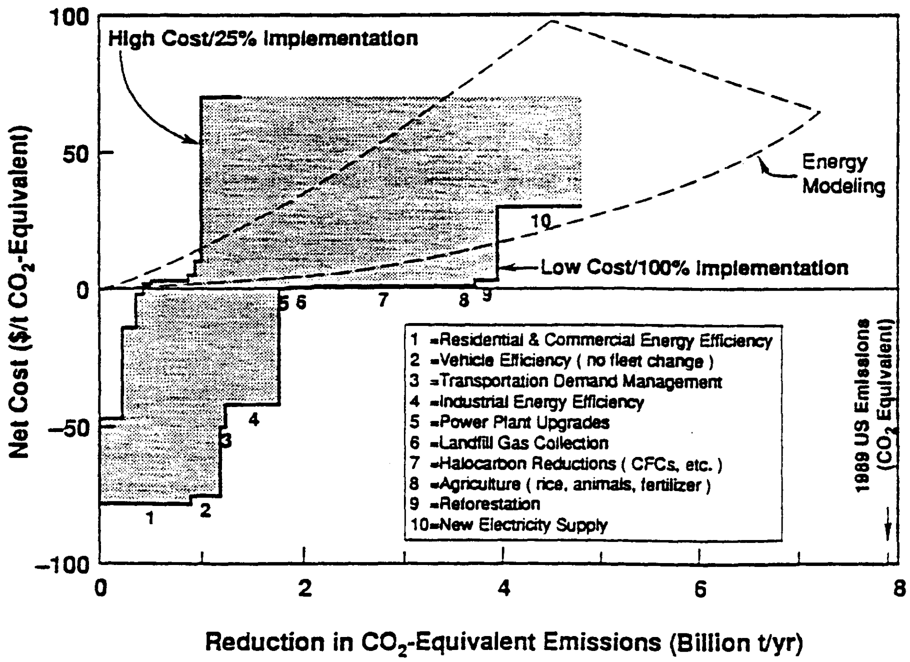

Figure 1 Cost-effectiveness versus emission reduction potential for various mitigation options. The results derived in this study are shown as steps for ten major categories of mitigation options ordered by cost-effectiveness. For each sector, "high" and "low" direct-cost estimates are combined with implementation rates of 25 and 100% of the maximum potential reduction for each measure to characterize the range of uncertainty. The energy modeling results that employ other methods of analysis are shown by the dashed lines encompassing a range of studies summarized by Nordhaus (W.D. Nordhaus, 1991. *American Economic Review* Vol. 81, No. 146). All costs are in constant 1989 dollars. Emissions are in metric tons (reproduced from Rubin et. al., 1992).

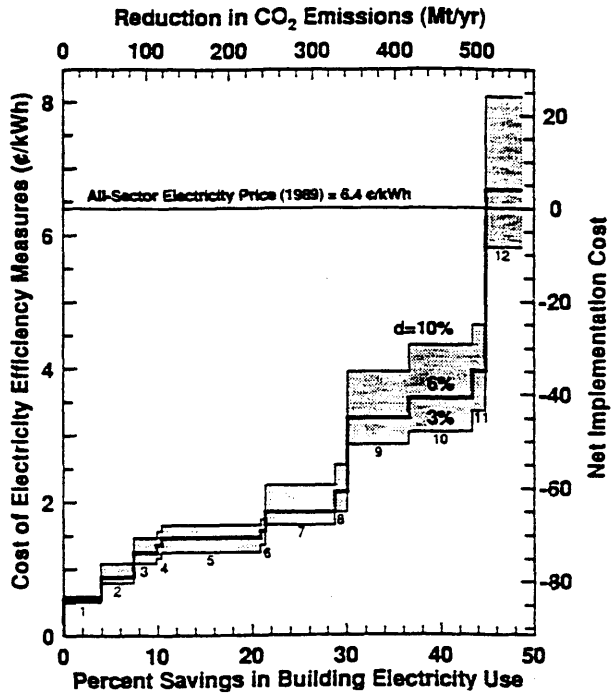

Figure 2 Representative marginal cost curve for building sector electricity use. Each step corresponds to the annualized investment cost of a given efficiency technology option[2], expressed in cents per kWh for real discount rates 3, 6, and 10%. Electricity savings for each option are given as a percent of total 1989 building sector electricity use. Eleven measures costing less than the average 1989 price of electricity (6.4 cents/kWh) would reduce building energy use by 734 BkWh (45%) at a net cost savings. The corresponding reduction in CO_2 emissions is based on the national average emission rate for 1989 (reproduced from Rubin et. al., 1992).

[2] 1 White roofs and trees; 2 residential lighting; 3 residential water heating; 4 commercial water heating; 5 commercial lighting; 6 commercial cooking; 7 commercial cooling; 8 commercial refrigeration; 9 residential appliances; 10 residential space heating; 11 commercial and industrial space heating; 12 commercial ventilation.

demonstrates a systematic approach to the problem. Eventually, effective policy may be built upon the conclusions.

1.2 Framing the Central Question

The central question of the thesis is: "What is the technological dynamic of the sector?" Or, "what drives, and what hinders efficiency technology diffusion in the residential sector?" Finer questions are: "What do models of innovation diffusion say about the propensity of configurational technology to be adopted in residential households?" "How does the federal regulation of building energy efficiency affect technology?" Associated questions are: "How has residential energy efficiency evolved over time, and what forces have been perceived to drive this evolution?" "What are the existing technical measures available to make built facilities more energy-efficient?" "How do some of these work?" One final question is: "How can technology be made to improve the energy efficiency of the residential sector?"

1.3 Research Methodology

Improving energy efficiency through the application of technology requires two activities. First, the process of, and forces that affect technology diffusion should be identified and understood. Second, using this understanding, appropriate policies should be designed. This thesis focuses on the investigative half of the process. By looking at two effects, the natural propensity of an important efficiency technology to diffuse and the effect on technology of a particular regulation, a preliminary characterization of the technological dynamic of energy efficiency in the residential sector is obtained. Under the guidance of the scientific method we would formulate a hypothesis, test it, modify it as suggested by the results of the test, and iterate the procedure until robust conclusions are reached. The hypothesis could be tested through experimentation or observation. But in this case we are constrained in various ways. The complexity of the problem does not point to an obvious verifiable hypothesis, nor even a single type of inquiry that would allow us to address the problem in a comprehensive way. For reasons of cost and logistics, conducting an experiment must be ruled out. In fact, the elaborate nature of the problem and the requirement that we rely on observation suggests using a case study approach. Drawing general and robust conclusions from one or several case studies is difficult (de Neufville, 1992), but possible, and in this case appropriate.

Case studies can be designed to test or apply existing theory, or to be part of the development of such theory (de Neufville, 1992). In order to test a theory using a case study, three steps are recommended: (1) state the theory; (2) state expectations about what we should observe if the theory is valid, and what we should observe if it is false; (3) explore the case (or cases) looking for congruence or incongruity between expectation and observation (Van Evera, 1996). For case studies designed to develop a theory, three different steps are recommended: (1) search for "associations between phenomena" and testimony of people directly involved as to their motives and beliefs; (2) ask: "of what more general phenomena are these specific cases and effects examples?" (3) frame various alternative cause and effect scenarios. These represent theories which can be further tested (Van Evera, 1996).

This research will incorporate both case study uses. For our cases to act in a theory-testing capacity, Chapter 4 summarizes a variety of models of the innovation and diffusion processes. The applicability of this theory will be highlighted and evaluated at relevant points in our cases. The logic of providing and later applying these models is borrowed from Morgan's analysis of the organization. The first step of his method is to "produce a diagnostic reading of the situation being investigated, using different metaphors to identify or highlight key aspects of the situation. The second step is to make a critical evaluation of the significance of the different interpretations thus produced" (Morgan, 1986, pp. 322). This provides a systematic way of interpreting a complex problem.

At the same time that various models are being applied in the case studies, the case information will be examined for "associations between phenomena" to build a comprehensive interpretation of energy efficiency investment in the residential sector. For example, the institutional structure within which decisions are made might suggest a certain pattern of diffusion or the existence of a particular barrier to adoption. Three particular methods explained by Van Evera (1992) may be useful: controlled comparison, especially the "method of agreement" (in which cases with different characteristics and similar values on the study variable are compared to generate candidate causes or effects of the variable); congruence procedure (in which one seeks correlation between the study variable and other phenomena, nominating well-correlated phenomena as new independent variables); and process tracing (in which the causal process by which the outcome was produced is traced, "at each stage inferring from the context what caused the cause").

In summary, the research will draw conclusions about the factors that govern the diffusion of residential energy efficiency technology based on case studies that are largely theory-testing, but also theory-creating. Once healthy case study conclusions are arrived at, a general characterization of the sector is achieved through induction. That is, by looking at some specific examples I make an inference about the nature of the sector generally.

The desire to make general inferences about the nature of the sector implies that the case studies should be carefully chosen. The distribution of energy consumption in the residential sector breaks down according to the following uses in the United States (measured in quadrillion Btu; from EIA, 1995):

space heating	5.32
appliances	2.40
water heating	1.83
air conditioning	0.46.

In the first case study, I look at the diffusion of passive solar systems, a configurational technology that reduces heating loads. In fact, when properly implemented, this measure can cost-effectively reduce space heating energy consumption by 50 percent, in an end-use sector that is responsible for more than half of all residential building energy use[3]. So although passive solar systems represent only one technology, they are an important one. Furthermore, it will become clear that several variables that govern the diffusion of this technology are relevant to a large number of other, configurational energy-efficient technologies. The second case study looks at a piece of federal regulation, the *National Appliance Energy Conservation Act of 1987*, and how affects the energy-efficiency of household appliances, which used 24 percent of residential energy 1993. This represents the largest end-use after space heating, and the share is rising. Appliance technology is thus also a fruitful area for us to explore in characterizing the dynamics of technology in the residential sector.

Passive solar design and energy-efficient appliances span a wide range of requirements for making an inferential argument. Each technology has large potential effects in one of the two largest end-use categories. The cases are thus important. In the context of residential buildings, one is systems- based, the other component-based. The cases thus cover two extremes that are governed by different effects in their diffusion. One technology is governed by local building codes and the other by federal-level agency rulemaking. The cases also thus prompt a discussion of two very different types of control over energy use and efficiency in buildings. The range and representativeness of the considerations required in these cases make them solid building blocks in an inductive argument.

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[3]Although in appropriate buildings this technology has massive potential, this is not necessarily so in all buildings. Issues such as community layout and development density constrain the applicability of the technology. These and other considerations will be discussed in the passive solar case study section.

1.4 Outline

Having looked at the motivations for research, the central questions and the research methodology, the remainder of the thesis is structured in the following manner. Chapter 3 examines the historical evolution of residential energy use and the forces that drive this evolution. This serves to verify that technology is an important determinant of efficiency and to highlight the importance of the topic: the United States is the world's largest emitter of greenhouse gasses, and the residential building sector is responsible for a major portion of this total. Chapter 4 describes models of technological innovation and technology diffusion that are employed later in assessing the technological dynamic of the sector. Chapter 5 looks at residential energy efficiency technology. Overviews of building systems, residential energy efficiency technology, passive solar systems, and energy-efficient appliances are provided. Chapter 6 is a case study of the diffusion of passive solar technology. The technology is analysed using the innovation and diffusion models summarized in Chapter 4. Here it is revealed that the configurational nature of the technology slows its diffusion. Chapter 7 discusses the effect of regulation on technology, with a particular focus on the *National Appliance Energy Conservation Act of 1987*. The effect of building codes is also discussed. Chapter 8, using the results of the Chapter 6 and 7 analyses, characterizes the dynamics of technology in the sector. It then outlines how a technologically proactive strategy to improve residential energy efficiency can be framed.

References

ASHFORD, Nicholas A., Christine Ayers, and Robert F. Stone, 1985. "Using Regulation to Change the Market for Innovation," *Harvard Environmental Law Review*, Vol. 9, No. 2, pp. 419-443; 462-466.

EIA (Energy Information Administration), *Annual Review of Energy 1995*.

de NEUFVILLE, Richard, 1992. *Thesis and Report Preparation: Some General Guidelines*. Technology and Policy Program, Massachusetts Institute of Technology, Cambridge, MA, 86 pp.

HIRST, Eric and Marilyn Brown, 1990. "Closing the efficiency gap: barriers to the efficient use of energy," *Resources, Conservation and Recycling*, 3, pp 267-281.

LIDDLE, Brantley (PhD. candidate, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology), 1996. Personal Communication.

MORGAN, Gareth, 1986. *Images of Organization.* Sage Publications, Newbury Park, CA, 421 pp.

PEZZEY, John, March, 1989. "Economic Analysis of Sustainable Growth and Sustainable Development," World Bank Environmental Department Working Paper No. 15, Washington, D.C.

PRINN, Ronald G. (Co-Director, Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology), 23 January, 1997. Independent Activities Period Lecture to the MIT community.

REINER, David (Ph.D. candidate, Department of Political Science, Massachusetts Institute of Technology), March, 1997. Personal communication.

ROSENBERG, Nathan, 1986. "The Impact of Technological Innovation: A Historical View," from *The Positive Sum Strategy: Harnessing Technologies for Economic Growth*, ed. by Ralph Landau and Nathan Rosenberg, National Academy Press, Washington, D.C., pp. 17-32.

RUBIN, Edward S. et. al., 1992. "Realistic Mitigation Options for Global Warming," *Science* Vol. 257, pp. 148-149, 261-266.

SKOLNIKOFF, Eugene B., Summer 1990. "The Policy Gridlock on Global Warming," *Foreign Policy* No. 79, pp. 77-93.

SLAUGHTER, Sarah, Spring, 1997. Innovation in Construction (class taught at the Massachusetts Institute of Technology), Cambridge, MA.

VAN EVERA, Stephen, 1996. *Guide to Methodology for Students of Political Science.* Defense and Arms Control Studies Program, Massachusetts Institute of Technology, Cambridge, MA, 70 pp.

YANG, Lynn (M.S. candidate, Technology and Policy Program, Massachusetts Institute of Technology), March, 1997. Personal communication.

2

Introduction

This thesis characterizes the *technological dynamic* of the residential building sector. It identifies the forces that drive and hinders technology diffusion. For a long time, the residential sector was scorned for lacking a progressive technology orientation (documented in, for example, Ventre, 1979), and subject to all manner of ways to bring it "in to the 20th Century."[1] Noting and explicating the technological backwardness of the residential building sector has since fallen out of fashion. But this change in favour has not, unfortunately, coincided with a renewed or deepened understanding of the way that technology behaves in the sector. Some researchers continue to talk about sectoral *technology lag*, the phenomenon of slow adoption of new innovation and all manner of illogical behaviour, particularly in the realm of energy consumption. Others talk about barriers to the adoption of efficiency technology (for example, Hirst and Brown, 1990). But there has been little systematic examination of the forces that affect technology diffusion. This thesis aims to fill the gap. Although it is destined to fall short of a general characterization by nature of its limited scope, it does look at representative examples and, by inference, several broad conclusions about the sector are drawn.

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[1]For example, through the failed *Operation Breakthrough* (described by Slaughter, 1997) and *Civilian Industrial Technologies Program* (documented in Nelkin, 1971).

The first is that the very nature of certain residential building technologies militates against rapid diffusion. This was found to be the case with passive solar design. Because of its configurational, application-specific nature, the innovation process must be repeated in virtually every instance of adoption, creating an arduous diffusion process. This effect is very likely to dominate in a host of other early-stage, configurational technologies -- precisely those through which it is easiest to make buildings energy-efficient.

The second conclusion is that regulation in the realm of building energy efficiency is not technologically proactive by any stretch of the imagination. Rather than recognizing the ability of technological improvement to improve, for example, the cost *and* energy efficiency dimensions of household appliances, regulation is confined to a static, cost-benefit balancing paradigm where the majority of the "facts" are dictated by a concentrated industry largely hostile to regulation.

The net result is not surprising: the residential building sector, though not mysteriously "backwards" as some claim, is not well-suited for rapid technology diffusion in the realm of energy efficiency. The history of sectoral energy consumption reflects this characteristic.

References

VENTRE, F. T., November, 1979. "Innovation in Residential Construction," *Technology Review*, pp. 51-59.

HIRST, Eric and Marilyn Brown, 1990. "Closing the efficiency gap: barriers to the efficient use of energy," *Resources, Conservation and Recycling* 3, pp. 267-281.

NELKIN, Dorothy, 1971. *The Politics of Housing Innovation: The Fate of the Civilian Industrial Technology Program.* Cornell University Press, Ithaca, NY, 124 pp.

SLAUGHTER, Sarah, 1997. *Innovation in Construction*, class taught in the Department of Civil Engineering at the Massachusetts Institute of Technology, Cambridge, MA.

3

Historical Energy Use in the United States

INTRODUCTION

This chapter strives to answer two questions. First, how has residential energy use evolved? Second, what forces drive this evolution? In this way, Chapter 3 puts our discussion of technology and energy efficiency in perspective: residential energy use is of major importance. It is also important to know what forces drive consumption in order to bound our discussion of the role of technology. The data and analysis presented demonstrate the significance of technology as a determinant of efficiency, partially by showing the structure of sectoral energy use in relatively fine detail, and partially by summarizing current understanding of the structure of residential energy use. In Chapter 6, the thesis analyses a technology that applies to the space heating end-use. In Chapter 7, the effect of regulation on another technology (and associated end-use), energy-efficient appliances, is analysed. The data presented here thus provide a means for the reader to judge the relative breadth and representativeness of these analyses.

Section 3.2, "Basic Concepts," provides on overview of common energy statistics. Data on consumption trends in the residential sector are presented in Section 3.3. A subsectoral disaggregation of residential energy use and a review of some basic relationships are provided in 3.4. Section 3.5 discusses the determinants of residential energy consumption and efficiency.

3.1 Basic Concepts

The concepts of system use and system efficiency suggest different types of measurement. The most obvious measurement type is total consumption, recorded as a flow of energy consumption per year or other time unit. Energy consumption is referred to differently depending on one's position in the production-conversion-consumption cycle. Different labels include:

Label	*Energy Form (example)*	*Conversion Process*
resource	crude oil in ground	
recoverable reserves	crude oil in ground	discovery
primary energy	crude oil extracted	production well
secondary energy	kerosene	refinery
delivered energy	kerosene purchased	distribution and marketing
utilized energy	heat absorbed	cooking

(Leach and Gowen, 1987).

Primary energy measures "the potential energy content of the fuel at the time of initial harvest, production, or discovery prior to any type of conversion." Secondary energy "differs from primary energy by the amount of energy used and lost in supply-side conversion systems." Delivered energy "records the energy delivered to or received by the final consumer, such as a household." Utilized energy measures "the amount of work or utilized heat to perform a specific task" (Leach and Gowen, 1987).

In the residential sector, energy is monitored by source as well as by end use. Typical sources and end-uses such as those used in the U.S. Department of Energy's *Residential Energy Consumption Survey* include:

Sources	*End Uses*
electricity	space heating
natural gas	air conditioning
fuel oil	water heating
kerosene	refrigerator
liquefied petroleum gas	appliances.

Resources and reserves are measures as stocks, and primary, secondary, and delivered energy are measured as flows. Intensity or efficiency is measured by normalizing consumption to a non-energy value. For many energy-using processes, it is a simple matter to decompose total energy consumption into the product of output and efficiency. For example, automobile fuel consumption is roughly equivalent to the product of car mileage and miles traveled. In the residential sector this decomposition is more difficult. Total consumption would be the product of services delivered and the energy-efficiency of service provision, but these data are often difficult to define, unavailable, and difficult to manage over the wide range of energy-using services employed in buildings.

Nevertheless, there exist various indices for residential energy efficiency. We can, for example, examine trends in energy consumption per square foot, per household, per person, per person per square foot, per unit of family income, or as a fraction of expenditure. Energy consumption or expenditure per square foot is often normalized to heating degree days (HDD) or cooling degree days (CDD) to account for climatic differences[1]. Some basic sectoral data are presented in Section 3.3.

[1]The Energy Information Administration *Annual Review of Energy 1995* defines CDDs as the number of degrees per day that the daily average temperature is above 65 degrees Fahrenheit, where the daily average temperature is the mean of the maximum and minimum temperatures for the 24 hour period. Conversely, HDDs are defined as the number of degrees per day that the daily average temperature is below 65 degrees, with the daily average temperature computed in the same way.

3.2 ECONOMY-WIDE ENERGY USE

In an international context, the United States is a massive user of energy in residential buildings. The magnitudes of residential energy consumption in the United States, Japan, and Europe are compared in Figure 3. Figure 4 and Table 1 describe the evolution of total residential delivered energy use and changes in residential energy intensity (by population), respectively.

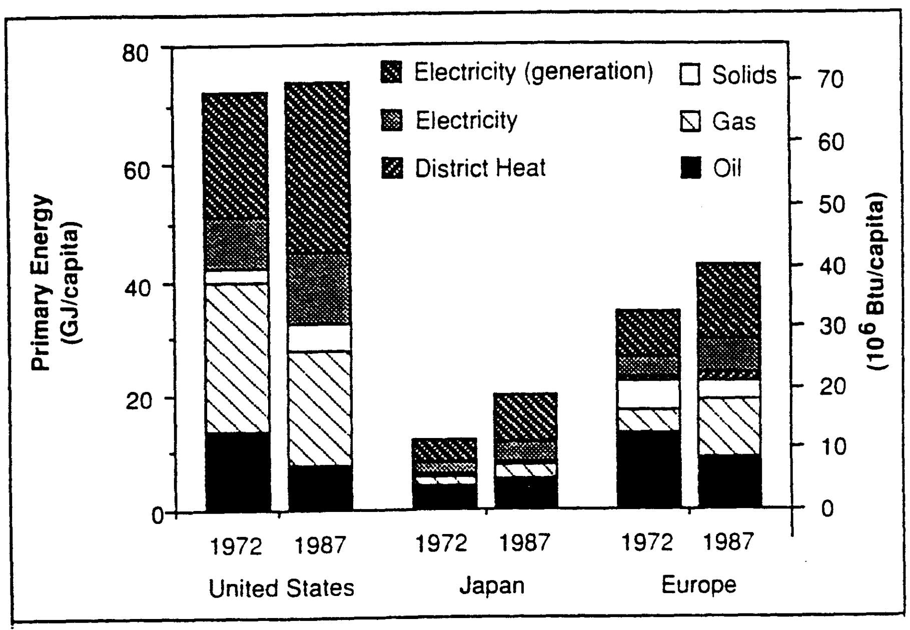


Figure 3 Primary residential energy demand in the United States, Japan, and Europe (West Germany, France, Italy, the United Kingdom, Denmark, Sweden, and Norway) (note 1 GJ = 0.958 * 10^6 Btu) (from Ketoff and Schipper, 1991).

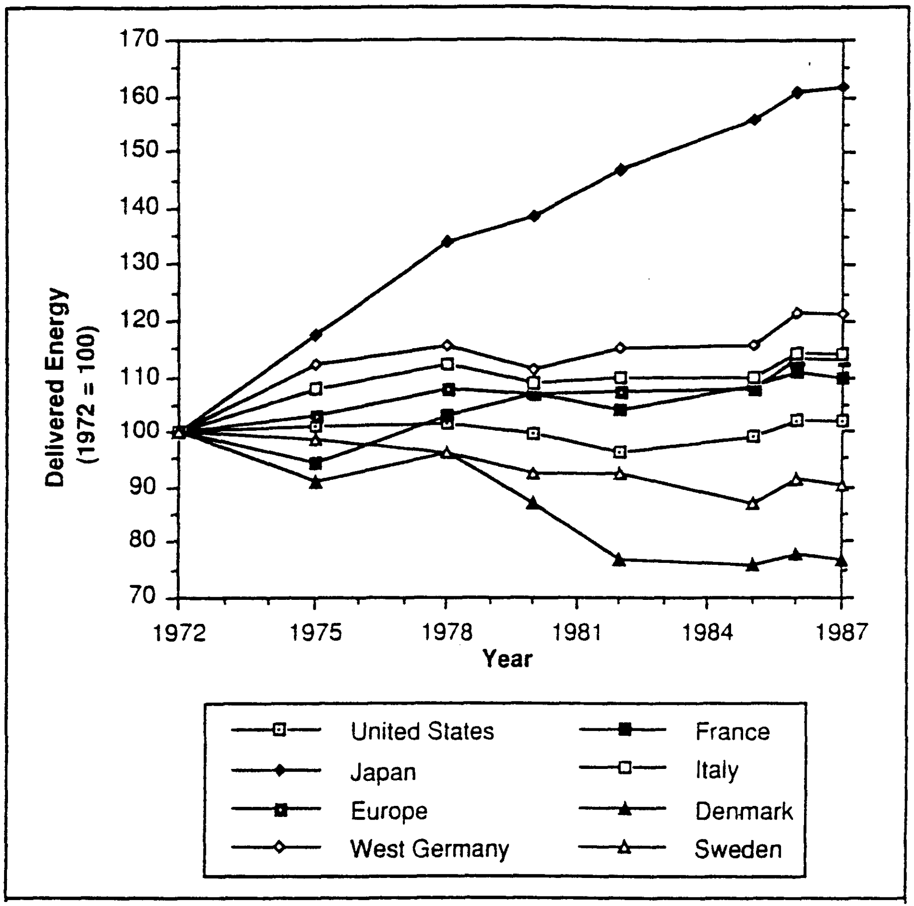


Figure 4 Changes in total residential delivered energy use (from Ketoff and Schipper, 1991).

Table 1 Changes in residential energy use (useful energy), population, and aggregate intensity between 1972/73 and 1988 (total % change) (Europe-4 includes West Germany, France, the United Kingdom, and Italy; Scandinavia-3 includes Sweden, Norway, and Denmark; OECD-9 includes Europe-4, Scandinavia-3, the United States, and Japan)(from Schipper and Myers, 1992).

	Energy use[a]	Population	Energy per capita[a]
United States	+3	+16	−11
Japan	+78	+13	+59
Europe-4	+16	+3	+12
Scandinavia-3	+8	+4	+0.4
OECD-9	+10	+10	0

[a] Useful energy.

For analytical purposes, the U.S. Department of Energy breaks down total energy consumption into industrial, transportation, and residential and commercial end-use sectors based on surveys to energy suppliers and marketers. Sectoral time series 1949 - 1995 are shown in Figure 5.

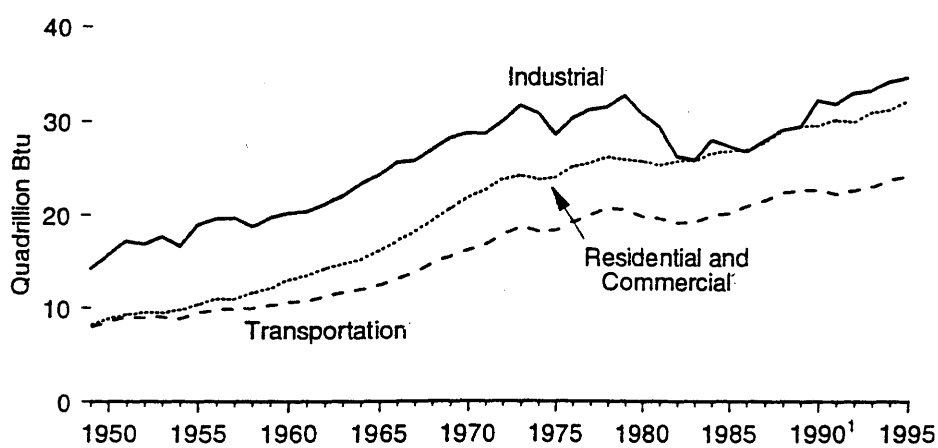


Figure 5 Energy consumption by end-use sector 1949-1995[2] (from EIA *Annual Energy Review 1995*).

[2]The report notes that these data series are subject to a discontinuity between 1989 and 1990 due to expanded coverage of non-electric utility use of renewable energy.

Residential buildings in particular consumed 17 623.2 trillion Btu in 1994. The 1970-1994 time series for the residential sector is shown in Figure 6.

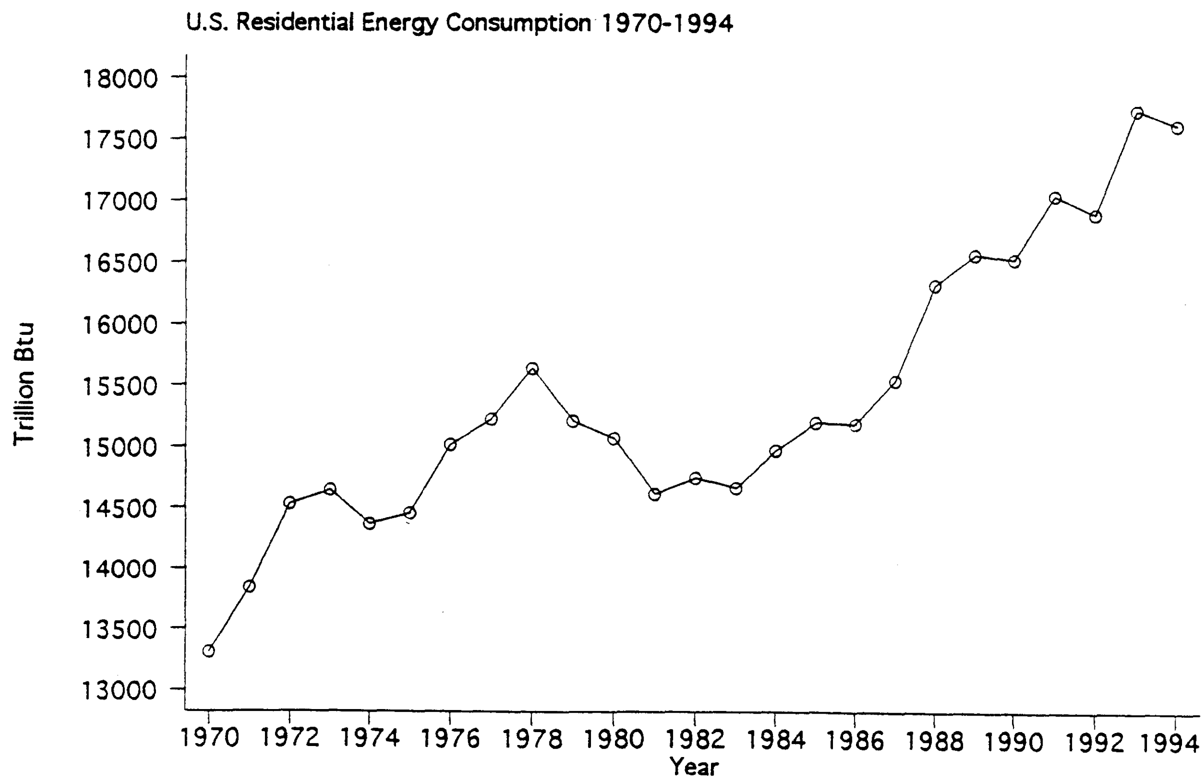


Figure 6 Residential energy consumption 1970-1994 (source: EIA *State Energy Data Report 1994*).

Consumption by all households 1978-1993 is shown in Figure 7, and consumption per household is shown in Figure 8.

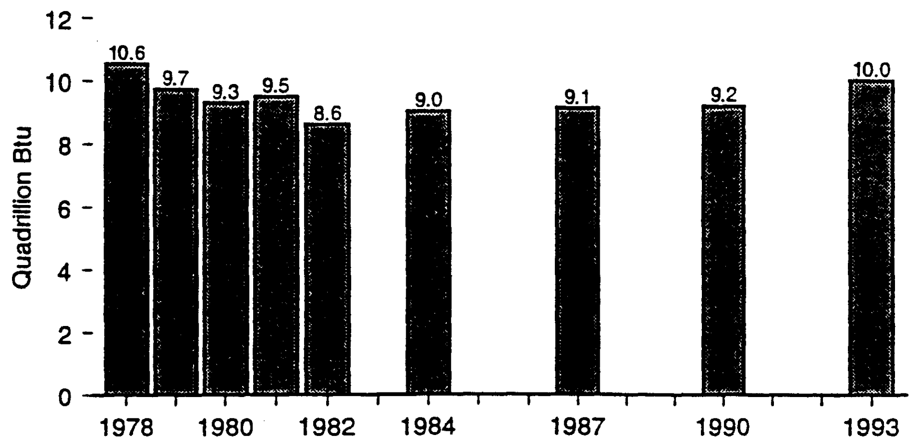


Figure 7 Energy consumption for all households, selected years 1978-1993 (from EIA *Annual Energy Review 1995*).

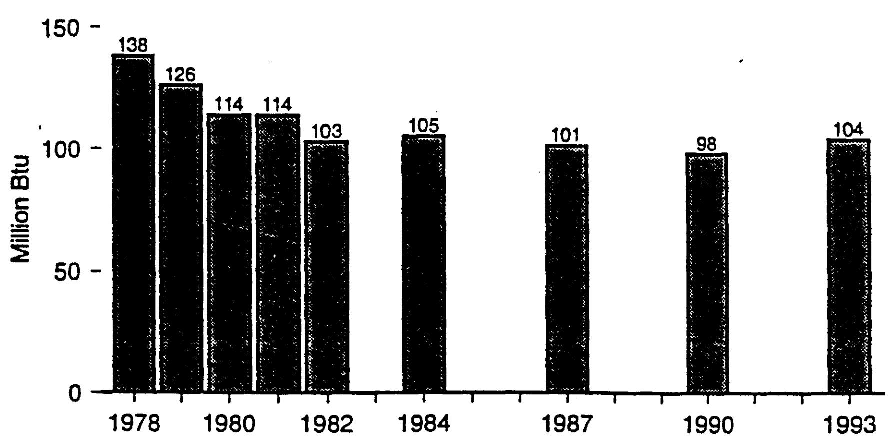


Figure 8 Energy consumption per household, selected years 1978-1993 (from EIA *Annual Energy Review 1995*).

Finer data on residential energy consumption are also available; some of these are presented in Section 3.3.

3.3 RESIDENTIAL ENERGY USE

A. *Overview*

Aggregate residential energy use breaks down by energy source (shown selected years 1978-1993 in Table 2) and by end-use (shown selected years 1978-1993 in Table 3). Graphic snapshots of consumption by end-use and source in 1993 are shown in Figures 9 and 10, respectively. Some basic relationships are also apparent in U.S. Department of Energy surveys of residential energy use. These are discussed in Subsection B.

Table 2 Household energy Consumption by Source (quadrillion Btu), Selected Years 1978-1993 (Source: EIA *Annual Energy Review 1995*).

	1978	*1980*	*1981*	*1982*	*1984*	*1987*	*1990*	*1993*
natural gas	5.58	4.94	5.39	4.77	4.98	4.83	4.86	5.27
electricity	2.47	2.46	2.48	2.42	2.48	2.76	3.03	3.28
fuel oil	2.19	1.55	1.33	1.14	1.26	1.22	1.04	1.07
LPG	0.33	0.36	0.31	0.29	0.31	0.32	0.28	0.38
total	10.57	9.31	9.51	8.62	9.03	9.13	9.21	10

Table 3 Household Energy Consumption by Sub-sector (quadrillion Btu), Selected Years 1978-1993 (Source: EIA *Annual Energy Review 1995*).

	1978	*1980*	*1981*	*1982*	*1984*	*1987*	*1990*	*1993*
space htg.	6.94	5.17	5.44	4.82	5.13	4.93	4.79	5.33
air cond.	0.31	0.32	0.33	0.3	0.33	0.44	0.48	0.46
water htg.	1.53	1.86	1.69	1.56	1.63	1.64	1.67	1.82
appliances	1.77	1.97	2.05	1.95	1.92	2.1	2.27	2.4
total	10.55	9.32	9.51	8.63	9.01	9.11	9.21	10.01

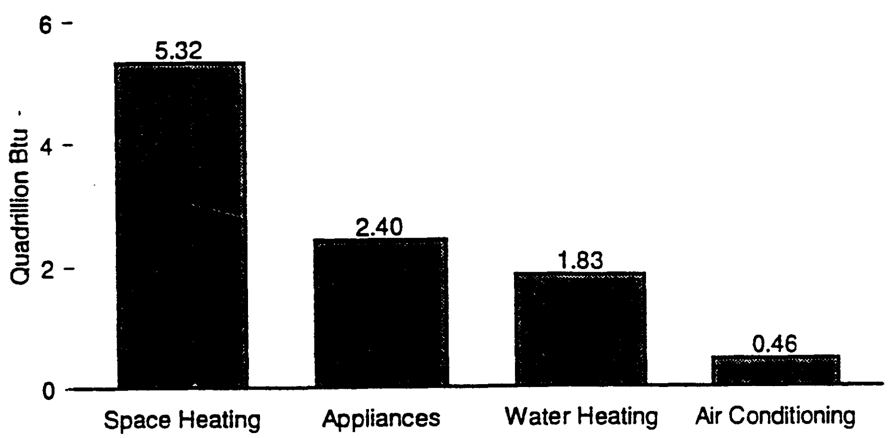


Figure 9 Residential energy consumption by end use, 1993 (source: EIA, 1995).

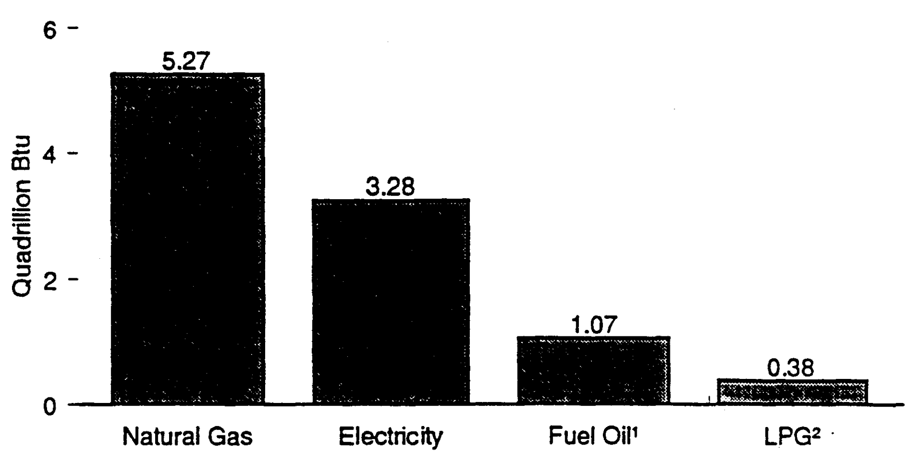


Figure 10 Consumption by energy source, 1993 (Source: EIA, 1995).

B. Basic Relationships

Detailed data gathering by the U.S. Department of Energy (1995) reveals a variety of basic relationships between *energy consumption per household* and variables like family income, household square footage, etc. These are useful as background.

As might be expected, space heating is positively correlated with number of heating degree days and lack of cooling degree days, and vice-versa for air conditioning. All uses are positively correlated with total number of rooms and total area of heated floorspace. Energy use per household is greater for owned than for rented units for all end uses. Energy consumption for air conditioning is negatively correlated with building age, while age is positively related to consumption for water heating. Energy consumed for space heating is strongly associated with building age, ranging from an average of 85.7 million Btu for houses built in 1939 or earlier to an average of 40.1 million Btu per household for buildings built between 1991 and 1993. All uses display a very strong association with family income. Total energy consumption is correlated with householder age and householder education.

3.4 Components of, and Forces Driving Residential Energy Consumption and Efficiency

Different studies strive to understand the determinants of residential energy consumption and efficiency in different ways. The U.S. Department of Energy *Residential Energy Consumption Survey 1993* (RECS) notes the effects of new additions to the housing stock, weather, and increased use of appliances as important components of change. "New homes (built between 1988 and 1993) use energy at a rate that is 82 percent of the rate used by homes built before 1980."[3] Figure 11 plots the housing stock and additions to the stock over time. Currently, additions to the stock run approximately one percent of the total per year.

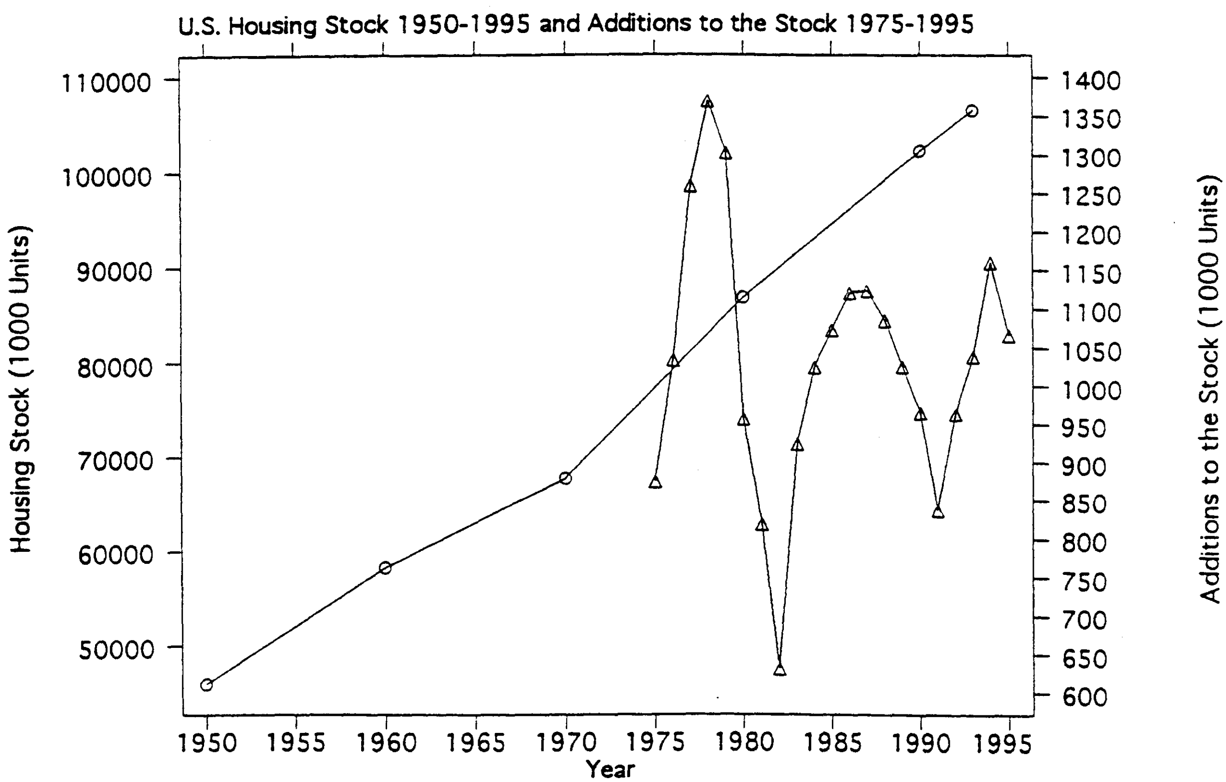


Figure 11 U.S. housing stock in selected years (left axis, source: U.S. Bureau of the Census, 1996) and additions to the housing stock (right axis, NAHB, 1997).

The RECS also noted the important effect of weather on energy consumption:

> Energy consumption in 1993 would have been nearly unchanged from consumption in the 1987 and 1990 survey years if the winter had been as

[3]The report attributes this to improved efficiency in space heating equipment and building shells.

> warm. The colder winter in 1993 led to an increase of 9 percent in natural gas consumption for space-heating and a 21-percent increase in electricity consumption for space-heating from 1990. Summers over the 3 survey years were about equally as warm and close to the 30-year average, so weather had little effect on energy consumption for air-conditioning. (U.S. DOE, EIA, 1995)

Increased use of appliances is also significant:

> For example, in 1980 only 14 percent of households used microwave ovens, but in 1993, 84 percent of households used one. Personal computers are another appliance that has become more common; in 1990, 16 percent of households had personal computers, a percentage that grew to 23 percent in 1993. (U.S. DOE, EIA, 1995)

The *Residential Energy Consumption Survey 1993* includes these effects among their "key findings" from their most recent data set. Other authors have looked at consumption data in slightly broader perspective, for example by placing U.S. consumption in international perspective.

Steven Myers (1987), a researcher at the Lawrence Berkeley Laboratory Energy Analysis Program, defines two types of energy-related variables, structural and behavioural. Structural variables refer to changes in the physical setting such as the geographic distribution of the population, household characteristics, and the state of buildings and their energy-using equipment. Behavioural variables refer to changes in the amount of time that people spend at home and their behaviour at home. Both structural and behavioural variables are influenced by the economic setting, the institutional setting (manifested in the orientation of governments, energy suppliers, and equipment manufacturers), demographic changes, and "the social psychological setting that influences household energy-related decisions and behaviour" (Myers, 1987).

Ketoff and Schipper (1991) define components of change in household energy use and then attempt to assign causes to these components. In a 1991 "bottoms-up" study, they identified the following components:

- structural changes (changing size of dwellings and varying types of housing);
- changes in equipment characteristics (types of furnaces, relative saturations of central heating systems and stove heating, and saturations and energy-related characteristics of appliances);
- changes in the characteristics of building shells;
- changes in household behavior;
- effects of fuel switching.

The associated causes include price changes, income changes, conservation programs, building and appliance standards, and new technologies.

In another study, Schipper and Myers (1992) identify change in home area per person, change in heating equipment, and ownership of major appliances as basic structural factors for residential energy use. The authors then cite household size, home occupancy, change in disposable income, and change in energy prices as some key factors in the evolution of residential energy consumption in OECD nations from the early 1970s through the late 1980s.

The distinction between components of change and causes of change is not always kept clear. For example, if Schipper and Myers (1992) label home area per person as a "structural" variable, should household size then not also be a structural variable or component of change rather than a cause? In reality, uncovering the factors that drive change in consumption and efficiency beyond a first approximation quickly becomes an idle game. The effect of individual variables cannot be discerned for lack of the ability to run an experiment or of the ability to observe a variable independently of a range of other relevant ones. Myers himself (1987) asserts that "it is difficult if not impossible to sort out the quantitative effect of the various changes in the structure of and behavior in the residential sector."

CONCLUSION

In the midst of this uncertainty, we can be sure that the effect of technological change is an important determinant of residential energy use and efficiency-- technology provides improved services with less energy in new construction, for example. This chapter demonstrated the importance of residential energy consumption in international and domestic contexts. It described the way that the evolution of residential energy intensity has been studied by other researchers. Finally, it demonstrated that taking a technology perspective is a fruitful way to look at the problem of excess residential energy consumption.

REFERENCES

EIA (Energy Information Administration), *Annual Review of Energy 1995.*

EIA, *State Energy Data Report 1994.*

EDMC, IEE (Energy Data and Modeling Center, Institute of Energy Economics, Japan), February, 1996. *EDMC Handbook of Energy and Economic Statistics in Japan '96,* The Energy Conservation Center, Japan.

KETOFF, Andrea and Lee Schipper, 1991. "Looking Beyond Aggregate Household Energy Demand: What Really Happened to Conservation," in Edward Vine and Drury Crawley, editors, *State of the Art of Energy Efficiency: Future Directions*, American Council for an Energy-efficient Economy, Washington, DC, pp. 229-265.

LEACH, Gerald and Marcia Gowen, 1987. *Household Energy Handbook: An Interim Guide and Reference Manual.* World Bank Technical Paper No. 67, Washington, DC.

MYERS, Steven, 1987. "Energy Consumption and Structure of the US Residential Sector: Changes Between 1970 and 1985," in *Annual Review of Energy* Vol. 12, pp. 81-97.

NAHB (National Association of Home Builders), 1997. "Characteristics of New Single-family Homes 1975-1995," at http://www.nahb.com.

OECD (Organisation for Economic Co-operation and Development), 1991. *Energy Efficiency and the Environment*, OECD/IEA (International Energy Agency), Paris, France.

RUBIN, Edward S., Richard N. Cooper, Robert A. Frosch, Thomas H. Lee, Gregg Marland, Arthur H. Rosenfeld, ad Deborah D. Stine, 10 July, 1992. "Realistic Mitigation Options for Global Warming," in *Science* Vol. 257, pp. 148-149; 261-266.

SCHIPPER, Lee and Dianne V. Hawk, April, 1991. "More efficient household electricity-use: An international perspective," *Energy Policy*, pp. 244-265.

SCHIPPER, Lee and Stephen Myers with Richard B. Howarth and Ruth Steiner, 1992. *Energy Efficiency and Human Activity: Past Trends, Future Prospects*, Cambridge University Press, Cambridge.

U.S. Bureau of the Census, 1996. *Statistical Abstract of the Unites States: 1996* (116th Edition), Washington, DC.

U.S. DOE, EIA (U.S. Department of Energy, Energy Information Administration), October, 1995. *Household Energy Consumption and Expenditures 1993.*

4

Models of Innovation Diffusion

Introduction

The unmistakable under-utilization of technology in buildings implies that technology can, and should, play a definite role in resolving our problems of excess energy consumption.

One goal of this thesis is to suggest how the power of technology can be invoked in improving the energy-efficiency of buildings. A discussion of technology is thus useful to understand it in its proper context. In fact, we must first explicate the nature and features of technology if we are to even understand the dynamics of residential energy efficiency and our potential role in improving it.

One caution is in order, however. The problem of profligate residential energy use has obvious complex human and political dimensions. Furthermore, technology is of circular nature: "it is only by the application of technology that we can cope with the consequences of technological change that has already occurred" (Benn, 1975; Benn, 1975 in Ehrenfeld, 1990). It is thus important to avoid the precipitate application of technology without careful regard to how it is likely to be used.

The *Oxford English Dictionary* defines *technology* as "the mechanical arts or applied sciences collectively; the application of (any of) these" (Brown, 1993). This definition does not tell the whole story. Certainly the application of mechanical sciences alone does not. As a useful product of human imagination, different forms of social organization should, for example, be considered technologies. A richer definition would be the application of human knowledge to a pre-specified end or need (Ehrenfeld, 1990; Ashford, 1997). Benn (1975) proposes:

> [Technology] has come to signify tools and their development and use in the broadest possible sense. It encompasses any systematic employment by man of the cause-and-effect relationship or empirical (cut-and-try) methods to achieve some desired purpose. The purpose of all technology can be generalized as an attempt to modify in some intended and desired way the relationship or compatibility of man and his environment.

Innovation refers to a subset of technology. An innovation represents the development of a new, usable, and non-trivial process, product or system change (Slaughter, 1997). The term is thus defined in relation to the context in which the new product, process, or system is applied; *new* can be defined by organization, industry, country, etc. *Innovation* should not be confused with *invention*, something that is demonstrably new or novel, but not necessarily useful.

Of course these definitions are alone inadequate. They provide a way for us to agree on what we are referring to. However, they are not rich or fine enough to allow us to explain how technology works or by what mechanism it acts or has effect. For this purpose, in-depth study of technology is required. This chapter describes views of technology and technological change in Section 4.1, various authors' concepts of innovation in Section 4.2, and various authors' concepts of the mechanics of diffusion in Section 4.3. These models are then applied to the case of passive solar technology in Chapter 6.

4.1 VIEWS OF TECHNOLOGY AND TECHNOLOGICAL CHANGE

Before we analyse technological processes like innovation and diffusion on the residential sector, some analysis of technology itself is in order. Karmali (1990) describes three views of technology that he employs in an analysis of U.S. Environmental Protection Agency pollution prevention policy:

> Technological determinism is based on the principle that technological developments have their own dynamics and constraints that determine the direction of change even when stimulated by external forces. Economic determinism considers the market and economic competition to be the main forces behind technological innovation. Essentially, this approach treats technology as a black box. Unlike the first two approaches, social constructivism attempts to move away from such unidirectional models and suggests that different social groups, such as the users of the technology and those potentially affected by it or its impacts, are able to exert influence on those who develop the technology. Any technological change is thus seen as the product of a dynamic interaction, rather than one driving force from inside or outside the firm.

In a discussion of the sociology of technology, Pinch and Bijker (1987) criticize the economic analysis of technological innovation as including "everything .. that might be expected to influence innovation, except any discussion of the technology itself." This may be the result of a certain degree of disciplinary bias. Management scientists premise their work on the idea that certain insights are transferable between organizations and management situations. Few are technologists that bring hands-on experience to the devices and processes that they are studying. In the words of Pinch and Bijker, the result is typically the description of an "arbitrary" technology development process that is insensitive to the "content of technological innovations." A common arbitrary technology development process is depicted in Figure 12.

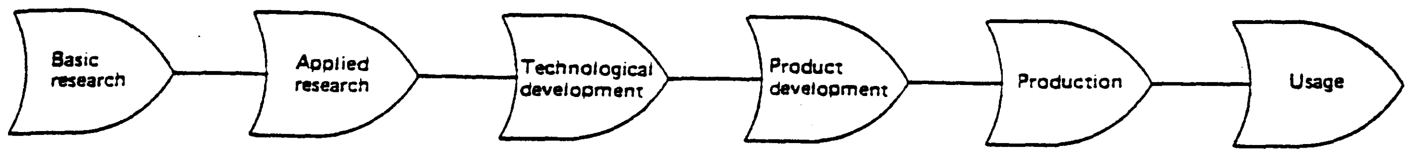


Figure 12 A six-stage model of the innovation process (from Pinch and Bijker, 1987).

The authors propose that the sociology of technology is a more fruitful mode of inquiry into this topic, and describe an emerging "social construction of technology" approach:

> [T]he developmental process of a technological artifact is described as an alternation of variation and selection. This results in a 'multidirectional' model, in contrast with the linear models used explicitly in many innovation studies and implicitly in much history of technology. Of course, with historical hindsight, it is possible to collapse the multidirectional model on to a simpler linear model; but this misses the thrust of our argument that the 'successful' stages in the development are not the only possible ones.

Yet the blanket characterization of the economic analysis of innovation as relying uniquely on a "black box" approach does not, in my opinion, give it fair consideration. Some of the economic models have a distinctly sociological bent, such as Dosi, 1982, and properly incorporate the notion of non-market factors and a selection environment. Furthermore, some incorporate other factors overlooked the social construction view, such as the association of technology with firm characteristics (Abernathy and Utterback, 1978) or a technology's region of impact (Henderson and Clark, 1990).

I rely largely on business economics models that are more sophisticated than the linear approach of which Pinch and Bijker are critical. Recall that we are interested in making a diagnostic reading of the forces that drive technology in the residential sector. Eventually, we would be interested in developing a framework for predicting and analyzing a decision units' (a contractor, for example) response to stimulus (an energy efficiency information dissemination program, for example). It should be emphasized that by no means must these models be applied monolithically. They serve well as an organizing framework and can be each evaluated on their own merits.

Each model of innovation that I describe captures particular phenomena that are useful for us to understand. The diffusion models are typically associated with a particular characterization of innovation. I am not attempting to explain the emergence of a particular technological innovation but rather, to understand innovation in its proper context. As a result, it is not necessary to belabour the question of whether its emergence can be better characterized by the technological determinism or social constructivist views, for example. It is important to recognize, however, the existence and potential effects of these views, while admitting that to some extent they are irreconcilable.

4.2 The Study of Innovation

Views of technology understood, the next step is to review a number of specific models of technological innovation. Eventually, we hope to characterize the technological dynamic of the residential building sector and then use the abilities of technology to improve the energy efficiency of the built environment. This section provides some tools with which to understand, and eventually motivate, the adoption of energy efficiency investments in the residential sector. The models described, whose labels are borrowed from Slaughter (1997), include region of impact, degree of effort, development path, timing, and technological momentum.

A. Region of Impact Analysis

Rebecca Henderson and Kim Clark (1990) devised a framework with which to define innovation and elucidate the relationship between innovation and firm structure. Their framework is focused on product development and consists of a two dimensional matrix. One axis is reserved for an innovation's impact on component design concepts and the other its impact on the linkage between core concepts, or the manner in which core concepts are combined to form a product. An innovation that results in unchanged links and core concepts is *incremental.* An innovation that results in unchanged links but overturned core concepts, "such as the replacement of analog with digital telephones" (Henderson and Clark, 1990) is *modular*. "Innovations that change the way in which the components of a product are linked together, while leaving the core design concepts (and thus the basic knowledge underlying the components) untouched" are *architectural.* Changed links and overturned component design concepts results in *radical* innovations. This system of categorization is shown in Figure 13.

Linkages between Core Concepts and Components	Core Concepts: Reinforced	Core Concepts: Overturned
Unchanged	Incremental Innovation	Modular Innovation
Changed	Architectural Innovation	Radical Innovation

Figure 13 A framework for defining innovation (from Henderson and Clark, 1990).

This model provides a way to characterize an innovation and often, to draw conclusions about the conditions under which it was developed and the likelihood of it being applied. In particular,

> architectural innovations destroy the usefulness of the architectural knowledge of established firms, and that since architectural knowledge tends to become embedded in the structure and information-processing procedures of established organizations, this destruction is difficult for firms to recognize and hard to correct (Henderson and Clark, 1990).

The authors attribute established firm difficulty to the action of three devices, "communication channels," "information filters," and "problem-solving strategies." These devices are described as required in the Chapter 6 analysis of passive solar technology.

B. Degree of Effort Analysis

Like Henderson and Clark, Donald Marquis provides us with a nomenclature for innovation. It includes: (1) the *complex system* such as a communications network or space mission, "characterized by thorough, long-range planning that assures that the requisite technologies will be available and that they will all fit together when the final development stage is reached;" (2) the *radical breakthrough* such as the jet engine or photocopier, "rare and unpredictable, ... predominantly the product of independent inventors or of research by firms outside the industry ultimately influenced by it;" (3) the *incremental or "nuts and bolts" innovation*, "ordinary, everyday, within-the-firm," and generally "paced by economic factors."

Marquis' more interesting contribution however, is a model of the process of innovation that describes a series of requisite firm-level activities. They are presented in a linear manner, with the possibility of feedback and iteration noted. It provides an overview of actions that at some point are executed in the development and introduction of a successful innovation. The process steps are: (1) *recognition* of technological feasibility and existing or potential demand; (2) *idea formulation*, or the creative act of fusing a recognized demand and technological feasibility into a design concept; (3) *problem solving* to translate the formulated concept into reality; (4) *solution* in the form of an invention or adoption if the problem is solved by input from another source; (5) *development*, the resolution of uncertainties of demand and production; (6) *utilization and diffusion* in the marketplace.

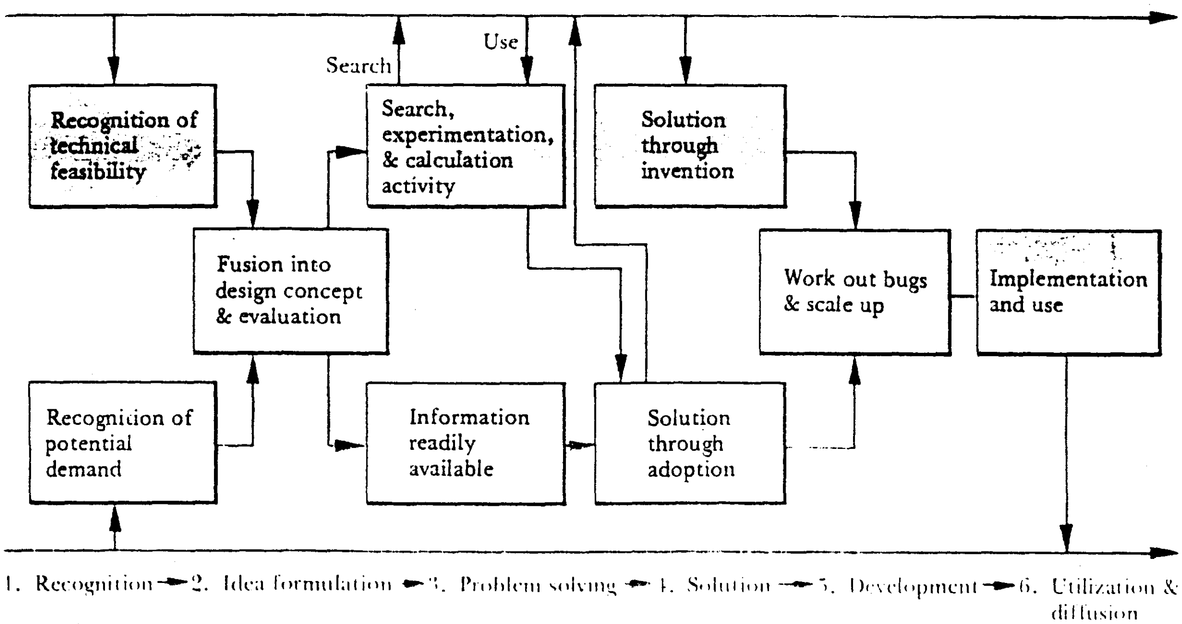


Figure 14 The process of innovation (from Marquis, 1988).

Although Marquis' reflections are perhaps less useful for characterizing innovation than the Henderson and Clark framework, his interpretation of the process is valuable. Eventually, we might use it to think specifically what must go on within a firm for innovation to occur.

C. Development Path Analysis

Giovanni Dosi (1982) also creates a framework with which to understand innovation inspired by Thomas Kuhn's description of the structure of scientific revolutions. At a given time, we view the world in a manner which conditions (and is conditioned) by our particular theories and methodologies of science. When our understanding changes, it sometimes does so discontinuously as a "paradigm shift."

Dosi proposes that technological innovation operates similarly. The key element of his model is the *technological paradigm.* It is defined as "an 'outlook,' a set of procedures, a definition of the 'relevant' problems and of the specific knowledge related to their solution," which "defines its own concept of 'progress' based on its specific technological and economic trade-offs" (Dosi, 1982, pp. 148). "Technology, in this view, includes the 'perception' of a limited set of possible technological alternatives and of notional future developments" (pp. 152). The paradigm determines the relevant "puzzles" (Kuhn, 1962 in Dosi, 1982). Technological paradigms include positive and negative *heuristics,* or "prescriptions on the *directions* of technological change to pursue and those to neglect" (pp. 152). Technological paradigms also feature an "exclusion effect," whereby the efforts and imaginations of the individuals and organizations are "blind" to technological possibilities outside the paradigm. However, because it is largely implicit in people's experiences and skills, which are themselves loosely defined, the technological paradigm must be viewed as an approximation.

Within the technological paradigm arises the *technological trajectory,* the "direction of advance within a technological paradigm" (Dosi, 1982, pp. 148). It consists of a "cluster of possible technological directions" and is formed by the pattern of "normal" problem solving ("progress") within a paradigm. It can be represented by "the movement of multi-dimensional trade-offs among the technological variables which the paradigm defines as relevant" (pp. 154).

Some features of technological trajectories described by Dosi are: (1) within each there is a technological frontier; (2) the probability of future advances is related to one's existing position relative to the technological frontier; (3) it is difficult or impossible to *a priori* assess the superiority of one trajectory over another. One feature which is likely to be particularly important in our analysis is the possibility of *complementarity* among trajectories, stemming from the likelihood of there being complementarity between different forms of knowledge, skills, etc.

A central premise of the model is that purely market-based models do not explain the emergence of new technological paradigms. Where technology has traditionally been defined as "a given set of factors' combination, defined (qualitatively and quantitatively) in relation to certain outputs," Dosi defines technology as a set of pieces of practical and theoretical knowledge, methods, experiences, and devices and equipment. Scientific advances, economic factors, institutional variables, and "unsolved difficulties on technological paths" are all important drivers of technological change. Dosi supports this premise with an elaborate and convincing explanation of the action of demand-based theories of innovation, and their weaknesses.

Dosi describes the "interactive mechanisms" that drive innovation as devices that "select" among technological paths. Economic forces and institutional and social factors "define more and more precisely the *actual* paths followed inside a much bigger set of possible ones" (Dosi, 1982, pp. 153). These might include such things as a concern for profitability or a government procurement program. He recognizes various specific variables: (1) the economic interests of the organization involved in research and development; (2) their technological history, fields of expertise, etc.; (3) institutional variables such as public agencies, the military, etc.; (4) public "political" forces such as broad interest in a space program. The existence of these factors points to the "general weakness" of market mechanisms in explaining technological change, particularly in the early stages of an industry.

This particular emphasis on the "stage" of an industry stems from the model's predicted effect of technological change on industrial structure:

> New technologies are selected through a complex interaction between some fundamental factors (search for new profit opportunities and new markets, tendency toward cost saving and automation, etc.), together with powerful institutional factors (the interests and the structure of existing firms, the effect of government agencies, etc.). Technical change along established technological paths, on the contrary, becomes more endogenous to the 'normal' economic mechanism. The distinction between the technological phases is likely to correspond historically to two different sets of features of an industry, related to its emergence and its maturity.

Dosi also distinguishes two roles for policy, the search for new technological paths and technological advance along a broadly determined technology. In particular, he notes the possible "focussing effect" of non-market interests such as military procurement, a particular energy-saving program, or a drive for national self-sufficiency in a particular sector. These he considers "forms of institutional intervention which stimulate technology 'starts' and competition" (pp. 160).

Dosi's model is useful for understanding technological change; it also sheds light on the process. The author sets out four requirements for using the model effectively: (1) "identify with sufficient precision the 'dimensions' which characterize each broad technological paradigm and differentiate it from others;" (2) "separate the periods of 'normal' technology from extraordinary search;" (3) "define the difficult puzzles' and unsolved difficulties of a technology which are often a necessary (although not sufficient) condition for the search for other ones;" (4) "describe the transition from one technological path to another and assess the factors which will allow the emergence of a 'winning' technology." This will be possible in some, but not all circumstances.

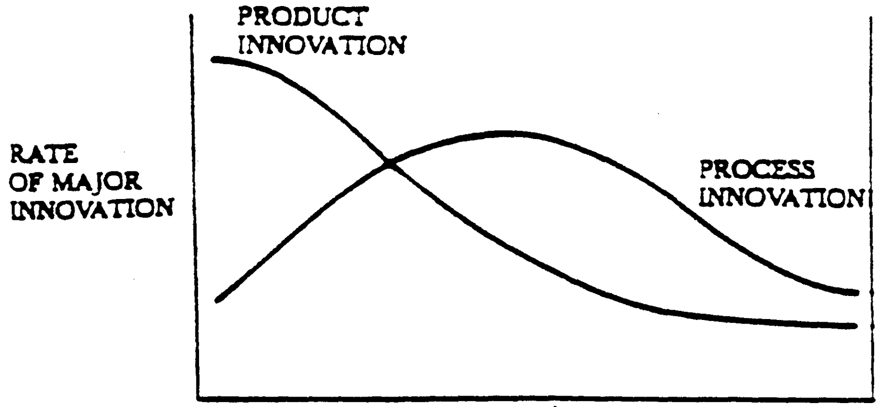
This model, aside from providing what I believe to be the most plausible description of technological innovation, is useful for meditating on the likelihood that certain circumstances will give rise to innovation, or that an innovation will be broadly introduced once it exists. What is the relevant trajectory? From what paradigm does it spring? What are the likely complementary trajectories? What "focussing devices" have affected this technology in the past? Are those in the making likely to be effective? What are the "interactive mechanisms" that affect a particular trajectory? Which among these are likely to be most important? These are the types of questions that Dosi allows us to ask. The ability will prove to be useful in the characterization of energy efficiency innovations.

D. Timing Analysis

William Abernathy and James Utterback provide us with an analysis of the relationship between firm structure and innovation. They define a spectrum of innovators between two extremes: small, entrepreneurial organizations, strong in product innovation, whose market advantage is realized through product functional performance, and large units "producing standard products in high volume" whose advantage is realized through economies of scale in production and the development of mass markets. An element of time is introduced in the model as organizations are believed to mature from pioneering to large-scale producers. The process is represented by the classic Abernathy and Utterback plot of the innovation process over time, shown in Figure 15.

A key concept of the model is the *dominant design*. "As a unit moves toward large-scale production, the goals of its innovations change from ill-defined and uncertain targets to well-articulated design objectives." Once the performance standards are established, "what we want is defined by what's already there" (Slaughter, 1997). This process is associated with a change in organizational structure towards more defined control and coordination, and consequently increased formality and layering of authority.

One of the implications of the model is that "units in different stages of evolution will respond to differing stimuli and undertake different types of innovation" (pp. 46). "We would expect new, fluid units to view as barriers any factors that impede product standardization and market aggregation, while firms in the opposite category tend to rank



Stage of Development	Fluid	Transition	Rigid
Predominant type of innovation	Frequent major changes in products	Major process changes required by rising volume	Incremental for product and process, with cumulative improvement in productivity and quality
Competitive emphasis on	Functional product performance	Product variation	Cost reduction
Innovation stimulated by	Information on users' needs and users' technical inputs	Opportunities created by expanding internal technical capability	Pressure to reduce cost and improve quality
Product line	Diverse, often including custom designs	Includes at least one product design stable enough to have significant production volume	Mostly undifferentiated standard products
Production processes	Flexible and inefficient; major changes easily accomodated	Becoming more rigid, with changes occurring in major steps	Efficient, capital-intensive, and rigid; cost of change is high
Equipment	General-purpose, requiring highly skilled labor	Some subprocesses automated, creating "islands of automation"	Special-purpose, mostly automatic with labor tasks mainly monitoring and controlling
Materials	Inputs are limited to generally-available materials	Specialized materials may be demanded from some suppliers	Specialized materials will be demanded; if not available, vertical integration will be extensive
Plant	Small-scale, located near user or source of technology	General-purpose with specialized sections	Large-scale, highly specific to particular products

Figure 15 The Abernathy and Utterback (1978) innovation process.

uncertainty over government regulation or vulnerability of existing investments as more important disruptive factors."

Abernathy and Utterback have observed what seems to be a common pattern: in their *Technology Review* article "Patterns of Innovation," they cite the histories of the semiconductors, long-range aircraft, and electric light-bulb industries as providing evidence for the type of evolution of firm structure that their model depicts. Indeed, the pattern that they observed is useful for thinking about the motivations that an industry is under and some of the pressures that they face. One does need to be careful because like many of the models described, they often assume a discernible product for the innovation. This condition may not necessarily be satisfied by the energy efficiency technologies under consideration.

E. Technological Momentum

One last model that we may draw upon is the concept of "momentum" for technology introduced by Foster (1986). He presents the idea of the "S-curve" of technological development. Early on, effort yields relatively little in the way of development because "lines of inquiry must be drawn and tested," technical problems abound, etc. Innovation then speeds up and progresses towards a "natural" technical potential. As this asymptote is approached, diminishing returns set in and the rate of development again slows down. The S-curve embodies the idea of technological discontinuity. The best way of addressing a given need, for example, will discontinuously "shift" from one mode or type of technology to another, often resulting in disruption to corporations who serve that need.

The Dosi model captures the idea of technological discontinuity in a more sophisticated manner than the "S-curve" concept. However, the S-curve explicitly relates the rate of technological development to product technical potential, which is interesting. Foster makes useful note of the potential "traps" that can leave a firm unprepared for technological discontinuity, including management culture, the misreading of market signals, and technological myopia. An interesting solution that he proposes is the research and development audit, a review based on the principle that research and development effort should be "proportional to potential for productivity and yield improvement" (Foster, 1986, pp. 224).

4.3 The Mechanics of Diffusion

In promoting improved efficiency through the use of technology, innovation is of little use without its counterpart, diffusion. Diffusion simply refers to the "wider adoption of innovation within an industry or industrial segment" (Karmali, 1990), but it is the process that ultimately imparts value to new technological knowledge. The analysis of diffusion takes the innovation as the unit of analysis and considers variation in adopting firms or organizations. The study of diffusion should be differentiated from the study of implementation, which takes the firms as the unit of analysis and considers variation between innovations.

Innovations are not equivalent units of analysis, and a particular innovation's characteristics determine in part its rate of diffusion. This is particularly true in the case of built facilities, where innovations can range from strongly component-oriented such as a more durable coating, to system-oriented such as a passive solar heating system, to process-oriented such as up-down construction.

Different models of diffusion have arisen in response to different types of technology and environment. I will describe the "classical" model (Mansfield, 1989; Rose and Joskow, 1990) and the "evolutionary" model (Cainarca et. al., 1989) for use in understanding the forces that drive and hinder diffusion of residential energy technologies.

A. The Classical Diffusion Model

In applying the classical model, we are interested in prognosticating the shape of the penetration "S-curve," a plot of the percentage of potential adopters who use a particular product over time. A typical S-shaped penetration curve is shown in Figure 16.

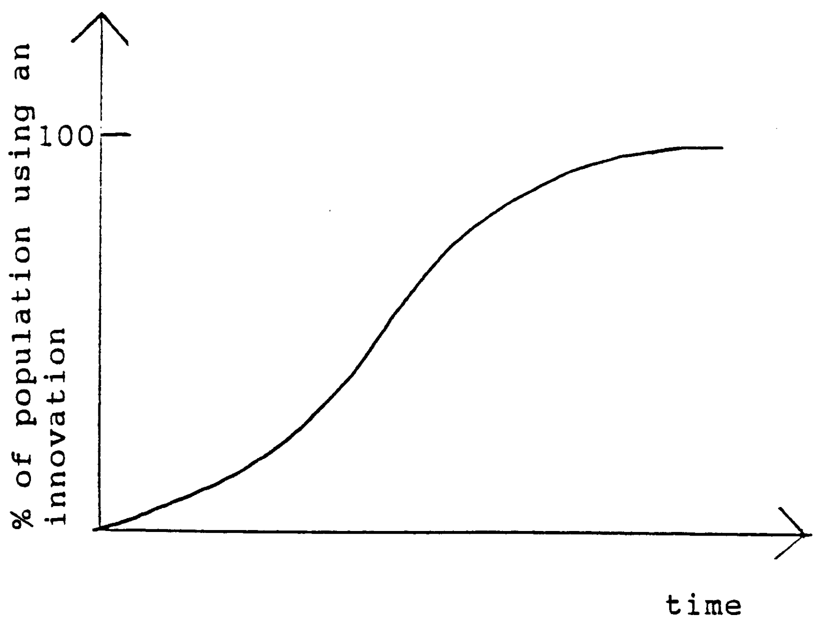


Figure 16 A representational penetration curve.

The classical model embodies the idea that there is a unique source for the innovation and that users obtain the innovation directly from this source. It is also referred to as a "centralized" model -- a central source provides to a multiplicity of users as shown in the following figure.

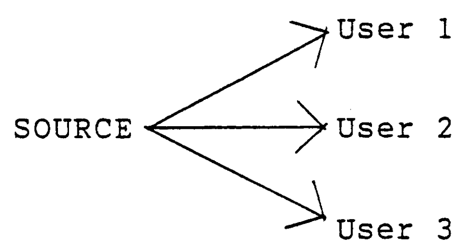


Figure 17 The centralized diffusion model (from Slaughter, 1997).

This model is often implicit in marketing studies where one might be interested in the diffusion of a new consumer product in a particular target market, for example. One needs to take care thinking about the factors that drive "classical" diffusion. Mansfield (1989) modeled a centralized process of innovation in a study of the diffusion of industrial robots in the United States and Japan. He identified the proportion of actual to potential users in a population of potential adopters, the average return from the innovation, and time from introduction in a particular industry and country as driving factors of the diffusion process. Rose and Joskow (1990) refined this model by separating the opportunity to adopt an innovation, manifested in the size of electric utilities adopting a particular generating technology, from the underlying firm propensity to adopt. This effect would certainly be difficult to quantitatively separate in the case of individual and household decision-making; we might use disposable income or some other factor.

The key difficulties in applying this model are: (1) defining the population of potential users; and (2) ensuring that the innovation in question is a discernible, unchanging product. These concerns prompt us to review an additional model prior to investigating diffusion in the residential sector.

B. The Evolutionary Diffusion Model

In contrast to the classical diffusion model, Cainarca et. al. (1989) propose that certain innovations diffuse according to an "evolutionary" pattern. The premise of this model is that the innovative aspects of diffusion cannot be differentiated (Slaughter, 1997). Technology is a changing entity, modified locally as it diffuses.

The authors rely on "Schumpterian" building blocks for their model. In brief, these are: technological progress consists of the simultaneous interaction of technical change and innovation diffusion; variety and rivalry drive the process; selection and imitation & learning mechanisms are at work; there is interaction between demand and supply; technology and market structure change endogenously in a network of feedback links. "A new innovation cycle originates from the emergence of a new *technological paradigm*" (Cainarca, et. al., 1989, after Dosi, 1982). Diffusion is affected by its "inherent peculiarities: the degree of appropriability; the potential for cross-fertilization between suppliers and users; technological complementarities; the expected profitability and cost of

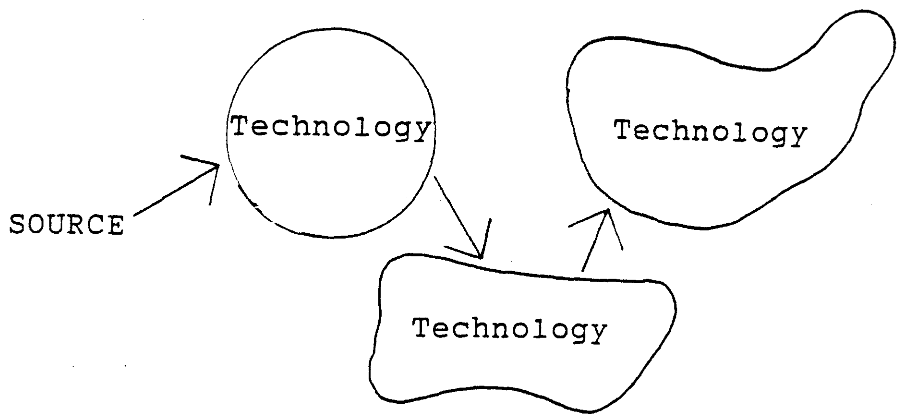


Figure 18 The evolutionary diffusion model (from Slaughter, 1997).

innovations. As a result, the phenomena of the localized search, the role of sunk costs avoidance, the focussing process, and the evolutionary efficiency of the selection environment are predicted to define the diffusion process. One implication of the model is the existence of a discontinuous learning effect (Slaughter, 1997). In conditions where application of an innovation are highly specific, it can be difficult for an innovation to move beyond mutation to where learning can accumulate.

In certain circumstances, a "decentralized" variant of the evolutionary model is used to analyze the diffusion of innovations. In this model, the user develops the innovation and then puts it to use. Intuitively, the mechanism of the decentralized model should, be close to that of the evolutionary model. The main difference is in its implication for the source of innovation, which now rests with the user.

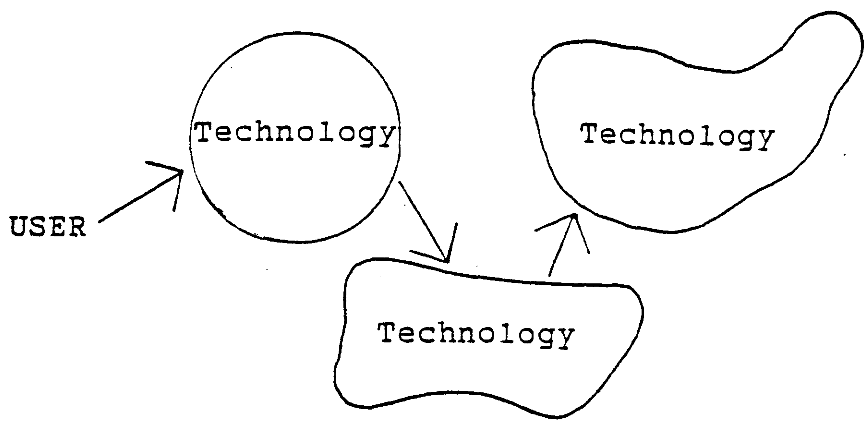


Figure 19 The decentralized diffusion model (from Slaughter, 1997).

C. Additional Determinants of Diffusion

Paul David, an economist at Stanford University, is primarily interested in process innovations, whose diffusion he explains as the cumulative investment decisions of individual firms. It is hypothesized that new technologies are introduced under conditions that make them profitable for only one part of an industry's firms. As the technology and its economic environment "coevolve," the appeal of the technology broadens and the technology is diffused (David, 1986). In turn, we summarize the relevant demand and supply side factors that he deems have an important effect on technology diffusion.

Three demand side diffusion phenomena are cited: (1) a wide distribution of responses to a technological innovation are possible on account of economic and technological "heterogeneity" within the population of potential adopters; (2) "new technologies are placed at a distinct disadvantage in competition with their predecessors whenever they come embodied in or are technically interrelated with indivisible capital goods that will burden the user with heavy fixed-cost charges (after Frankel, 1955; Salter, 1966 in David, 1986); (3) when gains from an innovation are significant only at "high throughput" rates (in a particular production process, for example) the scale of the innovating enterprise becomes key. Thus, economic reasons for differential adoption rates seem to exist. David argues that in the past, the role of poor information, risk aversion and the psychological difficulty of embracing change has been over-emphasized as effects on technology diffusion.

David's interpretation of important demand-side factors in the innovation adoption process leads us to a series of questions that it will be useful to ask when evaluating particular cases of energy efficiency technology. First, what are the technical and economic circumstances of the potential users? Second, what devices are the efficiency innovations competing with, and is the structure of this competition biased against new devices? Third, are any efficiency devices potentially responsive to scale, and does fragmented ownership retard their implementation?

David theorizes that three supply-side factors, "technology-access costs," affect the new technology diffusion process: (1) the cost of obtaining and processing information on new technologies; (2) the cost of obtaining the materials or equipment in which a new technologies is physically embodied; (3) the cost of specialized facilities, products, or services that are required in order to be able to exploit the innovation (David, 1986). Costs attributable to specialized products or services are especially likely to occur with innovations that display network externalities, for example the specialized operating system software required for a particular type of computer. These technology-access costs are likely to decrease over time for a variety of reasons such as coordinated or uncoordinated transfers of technical information and "learning-by-doing."

CONCLUSION

This chapter summarized three different views of technological change, informed by technological determinist, economic determinist, and social constructionist considerations. Innovation was distinguished from diffusion, and models for both processes were described. This model overview provides a framework for us to understand the technological dimension of residential energy efficiency and eventually, a means for us to effect improvements by identifying target policy variables.

REFERENCES

ABERNATHY, William J. and James M. Utterback, 1978. "Patterns of Industrial Innovation," *Technology Review*, Vol. 80, No. 7 (June/July).

ASHFORD, Nicholas A. and Charles C. Caldart, 1997. *Law, Technology and Public Policy*. Class taught in the Technology and Policy Program at the Massachusetts Institute of Technology, Cambridge, MA.

ASHFORD, Nicholas A., 1994. "An Innovation-Based Strategy for the Environment," in *The Debate Over Risk-based National Environmental Priorities*, edited by A. M. Finkel and D. Golding, Resources for the Future, Washington, D.C.

ASHFORD, Nicholas A., Christine Ayers, and Robert F. Stone, 1985. "Using Regulation to Change the Market for Innovation," *Harvard Environmental Law Review*, Vol. 9, No. 2, pp. 419-443; 462-466.

BENN, Anthony Wedgwood, 1975. "Technology and the Quality of Life," from *A Technology Assessment Primer*, ed. by L. Kirchmeyer et. al., Institute of Electrical and Electronics Engineers, Inc., New York, pp. 27-30.

BROWN, Lesley, Ed., 1993. *The New Shorter Oxford English Dictionary on Historical Principles*, Clarendon Press, Oxford.

CAINARCA, G. C., M. G. Colombo, and S. Mariotti, 1989. "An Evolutionary Pattern of Innovation Diffusion. The Case of Flexible Automation." *Research Policy* Vol. 18, pp. 59-86.

DAVID, Paul A. (1986). "Technology Diffusion, Public Policy, and Industrial Competitiveness," in Ralph Landau and Nathan Rosenberg, Eds., *The Positive Sum Strategy: Harnessing Technology for Economic Growth.* National Academy Press, Washington, D.C.

DOSI, Giovanni, 1982. "Technological Paradigms and Technological Trajectories," *Research Policy*, Vol. 11, pp. 147-162.

EHRENFELD, John R., 1990. "Technology and the Environment: A Map or Mobius Strip?" Paper prepared for the World Resources Institute Symposium *Toward 2000: Environment, Technology and the New Century*, June 13-15, Annapolis, Maryland.

FOSTER, Richard N., 1988. "Timing Technological Transitions," in Tushman and Moore, Eds., *Readings in the Management of Innovation* (Second Edition), Ballinger, Boston, MA, pp. 215-228.

GELLER, Howard and Steven Nadel, 1994. "Market Transformation Strategies to Promote End-use Efficiency," in Robert H. Socolow, Ed., *Annual Review of Energy and the Environment*, Vol. 19.

HENDERSON, Rebecca M. and Kim B. Clark, 1990. "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," *Administrative Science Quarterly*, Vol. 35, pp. 9-30.

KARMALI, Abyd, 1990. "Stimulating Cleaner Technologies through the Design of Pollution Prevention Policies: An Analysis of Impediments and Incentives." Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology and Policy at the Massachusetts Institute of Technology, Cambridge, MA, 199 pp.

MANSFIELD, Edwin, 1989. "The Diffusion of Industrial Robots in Japan and the United States." *Research Policy*, Vol. 18, pp. 183-192.

MARQUIS, Donald G., 1988. "The Anatomy of Successful Innovations," in Tushman and Moore, Eds., *Readings in the Management of Innovation* (Second Edition), Ballinger, Boston, MA, pp. 79-87.

NELSON, R. R. and S. G. Winter, 1977. "In Search of a Useful Theory of Innovation," *Research Policy*, Vol. 6, pp. 36-76.

NILSSON, H., 1992. *Summer Study on Energy Efficiency in Buildings* Vol. 6, pp. 179-187. American Council for an Energy-efficient Economy, Washington, D.C., cited in Geller and Nadel, 1994.

PINCH, Trevor J. and Wiebe E. Bijker, 1987. "The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other," from *The Social Construction of Technological Systems*, ed. by Bijker, Hughes and Pinch, MIT Press, Cambridge.

ROGERS, Everett M., 1995. *Diffusion of Innovations* (Fourth Edition). The Free Press, New York, 518 pp.

ROSE, Nancy J. and P. L. Joskow, 1990. "The Diffusion of New Technologies: Evidence from the Electric Utility Industry." *RAND Journal of Economics*, Vol. 21, No. 3, pp. 354-373.

ROSENBERG, Nathan, 1986. "The Impact of Technological Innovation: A Historical View," from *The Positive Sum Strategy: Harnessing Technologies for Economic Growth*, ed. by Ralph Landau and Nathan Rosenberg, National Academy Press, Washington, D.C., pp. 17-32.

SLAUGHTER, Sarah, 1997. *Innovation in Construction*, class taught in the Department of Civil Engineering at the Massachusetts Institute of Technology, Cambridge, MA.

WENK, E., 1979. *Margins for Survival: Overcoming Political Limits in Steering Technology*, Pergammon Press, referenced in Karmali, 1990.

5

Residential Energy Efficiency Technology

INTRODUCTION

In building a general characterization of the technological dynamic of the residential building sector, the technologies themselves should be understood. It is beyond the scope of this thesis to characterize each technology along the appropriate dimensions, cost, likely benefits, implied characteristics by innovation model, etc. Instead, I provide an overview of building systems (Section 5.1), including system components and system objectives. I then provide an overview of residential energy efficiency technology (Section 5.2), including the specific end-use categories in which energy efficiency opportunities are available and a list of existing, but underutilized technologies. Finally, I describe three technologies in detail: passive solar systems (subject of the Chapter 5 case study); horizontal-axis clothes washers; and urban trees and white roofs (as context).

5.1 OVERVIEW OF BUILDING SYSTEMS

Individual buildings are usually thought of as complex systems, or "assemblage[s] formed to satisfy specific objectives," "subject to constraints and restrictions," and "consisting of two or more components that are interrelated and compatible, each component being essential to the required performance of the system" (Merritt, 1982).

Specifically, a building's major component systems are understood to be the structural framing and foundations, the exterior and interior enclosure systems, and the electrical and mechanical systems (electric power and signal systems, lighting, plumbing, and HVAC (heating, ventilation, and air conditioning)) (Merritt, 1982; Ching, 1991). These subsystem definitions originate in the traditional activities of the construction trades that assemble buildings (Merritt, 1982).

A building's structural system consists of the foundations, which distributes building loads to the ground, the floor and roof decks, and the associated horizontal and vertical members that support the floor and roof decks. The exterior enclosure system provides privacy and the ability to control interior temperature and humidity, and generally consists of roofs and exterior walls (some of which may be, if load-bearing, simultaneously part of the structural system). The interior space enclosure system defines interior spaces and consists of non-structural walls, or partitions, interior finishes, doors, and glazing. The mechanical systems enable conditioning of the interior spaces, waste disposal, and water and electricity provision.

This ordering by subsystem is convenient when thinking about construction. However, it is clumsy for thinking about energy consumption. Energy consumption suggests a logic of sources and sinks, or fuel type and end-use. This in turn suggests a different way of thinking about building systems. For example, we might look at systems and components that affect the space conditioning load or the total electricity consumption.

Houses are "complex summations of space and service" (Kelly, 1959) that serve a multiplicity of functional objectives: the provision of shelter, comfort, personal space, etc. These objectives are not necessarily synergistic. An over-arching technology objective is that it be fit for occupation. Buildings are also usually designed as permanent systems. Hirst et. al. (1986) note that "buildings provide the temperature, humidity, and lighting necessary for people to live and work productively and in comfort." In *The Architect's Guide to Facility Programming*, the American Institute of Architects (Palmer, 1981) provides a long list of factors, human (comfort, safety, access, etc.), physical (uses, operations, energy use, etc.), and external (codes, standards, economics, climate, etc.), that influence the design of built facilities. However, objectives and constraints are not differentiated, nor are the factors' relative importance discussed. One might adopt as an energy-related list of building objectives as those deemed by Pellish (1990) appropriate for the application of solar energy: heating, cooling, lighting, moisture control, and indoor air quality. Whatever specific objectives one adopts, it is clear that buildings serve multiple and complex purposes and are subject to an equally complex set of constraints.

5.2 Overview of Residential Energy Efficiency Technology

The range of residential energy efficiency technologies is gargantuan. A comprehensive technology assessment considering the numerous relevant dimensions such as cost, appropriability, skill requirements for implementation, etc. is thus too great a task. This survey provides a brief overview, and demonstrates that the technologies chosen for the case studies are indeed representative of the efficiency opportunities available in the residential sector. It also highlights the massive, unrealized energy efficiency potential of the sector.

For each of the numerous and varied residential energy efficiency technologies, a large number of relevant attributes can be defined. Each attribute suggests a different system of organization, for example, by market opportunity (retrofit, new construction, replace on burnout, after U.S. OTA, 1982), by the logic of a particular innovation model (architectural, radical, incremental modular, after Henderson and Clark, 1990), by technology status (existing or emerging, after Nadel et. al., 1993), etc. I had initially proposed a nomenclature based on whether the innovation is systems- or component-based. However, this distinction becomes arbitrary as some technologies can be procured as components, but have systemic effects, like urban trees and high-albedo roofs. Other technologies like daylighting systems should be discussed in conjunction with the specification of artificial lighting components.

Because of these difficulties, I adopted a categorization based on a technology's effect on energy end-use, after the organization of the *E Source Technology Atlas Series*. This system breaks down efficiency technologies according to their relevance to building lighting, space cooling and air handling (mostly for application in commercial buildings), space heating, and appliances[1]. The breakdown is shown in Table 4.

Clearly it is too large a task to even enumerate the gamut of residential building energy efficiency technologies and the relevant considerations. Instead, I provide an additional list of technologies characterized by the American Council for an Energy-efficient Economy (ACE^3) as "existing," but "underutilized." ACE^3 is a non-profit organization based in Washington, DC dedicated to improving the energy efficiency of the economy in all sectors. Their technology assessments are progressive, but sober. Their "underutilized" technologies list can reasonably be considered to be a specific embodiment of inefficiency in the residential sector, even from the static and nummulary perspective of traditional economics. ACE^3 uses a slightly different nomenclature from E Source.

ACE^3 provides an equally long list of promising emerging technologies. Suffice it to say that there is no shortage of even newer efficiency technologies; it is not necessary to enumerate them. In the following section, I describe three existing technologies in detail: passive solar systems; energy-efficient appliances; and urban trees and white roofs. Passive solar systems will be the subject of detailed case studies later in the thesis; they are described here so that the technological dimensions of their diffusion and adoption may be

[1]The *E Source Technology Atlas Series* includes a volume on drivepower, but I have forgone it in this discussion because of its relative lack of importance to the residential sector. Some of the technologies (like passive solar) have the potential to fulfill several functions simultaneously, including some related to human health and comfort not explicitly mentioned in the E Source nomenclature.

Table 4 Residential energy efficiency technologies (after Houghton et. al, 1996; George et. al., 1996; Audin et. al., 1994; Shepard et. al., 1995).

- LIGHTING
  - Daylighting
  - Incandescent lighting
  - Full-sized fluorescent lighting
  - Compact fluorescent lamp technologies
  - High-intensity discharge lighting
  - Other sources
  - Lighting Controls
  - Lighting Maintenance
  - Specialized application lighting
- SPACE COOLING AND AIR HANDLING
  - Reducing Cooling Loads
  - Air-handling systems
  - Air-handling components
  - Alternative cooling
  - Unitary equipment
  - Chilled water systems
  - Electric chillers
  - Gas cooling
  - Cool thermal storage
- SPACE HEATING
  - Reducing heating loads
  - Residential mechanical ventilation
  - Distribution systems
  - Heating plants
  - Electric thermal storage
- APPLIANCES
  - Refrigerators and freezers
  - Cooking appliances
  - Clothes washers
  - Clothes dryers
  - Dishwashers
  - Other appliances

Table 5 Existing, but underutilized, residential energy efficiency technologies (from Nadel et. al., 1993).

- APPLIANCES
  - Induction cooktop
  - Cold-water laundry detergents
  - Halogen cooktops
- LIGHTING
  - Polarizing lenses
  - Skylights and clerestories for daylighting
  - Photovoltaics for remote lighting
  - Task tuning controls
- SHELL
  - Structural foam panels
  - Rammed earth
  - Light-coloured roofs
  - Insulated forms
  - Low-E/spectrally selective retrofit window films
- SPACE HEATING AND COOLING
  - Three function integrated heat pump
  - Heat pipe enhanced air conditioning
  - Integrated residential thermal storage
  - Air-to-air enthalpy recovery/exchange systems
  - Solar absorption air conditioning
  - Dual fuel heat pumps
  - Ducts in conditioned space
  - Ductless thermal distribution systems
  - Larger gauge electrical wire
  - Down-sized pool pumps with large piping
  - PV pool pumps
  - Dual path air conditioning systems
  - Larger heat exchangers
  - Two-speed air-conditioner and heat pumps
  - Variable-speed air-conditioners and heat pumps
  - Integrated chillers with heat recovery
  - Mini-split air conditioners
  - Ceramic thermal storage
  - Low face velocity/high coolant velocity cooling coil
  - Open-protocol energy management systems
  - Cold air distribution
  - Transpired un-glazed solar collector
- DOMESTIC HOT WATER
  - 90% efficient and above water heaters
  - Parallel piping
  - Alcohol pumped solar water heater
  - Tempering valve
  - Shower heads of 2.0 gpm and lower
  - Heat pump water heaters

understood and used in the analysis. The regulation of energy-efficient appliances is analysed in Chapter 7. One particular appliance technology, the horizontal-axis clothes washer, is described in this chapter to indicate of the type of the energy-efficiency opportunities that are available. The purpose of the urban trees and white roofs description is to provide an overall perspective on the scope of the building energy efficiency issue. This city-wide technology emphasizes that improved efficiency can be pursued at many different scales, and certainly not just at the level of upgraded building components.

5.3 SELECTED TECHNOLOGY DESCRIPTIONS

A. Passive Solar Systems

Passive solar technology uses solar radiation and natural thermal energy flow -- conduction, radiation, and natural convection -- to heat, cool, illuminate and ventilate. It is an *architectural* technology in two senses. First, it is manifested in the architectural design of a facility, through a building's configuration, materials specification, etc. Second, passive solar systems fit Henderson and Clark's definition of an *architectural* innovation: passive solar design uses standard building components in a non-standard way.

A passive solar heating system (1) admits sunlight; (2) converts it to heat upon absorption; (3) uses it directly for heating; *or* (4) transfers it to thermal storage and at a later time from storage to heating, by natural means (Morehouse, 1997). A passive cooling system transfers heat to environmental sinks (the ground, air, sky) using natural energy flow (*ibid.*). Passive daylighting uses sunlight, or solar beam radiation and skylight, "diffuse radiation scattered by the atmosphere," for "natural illumination of a building's interior spaces" (*ibid.*).

The contributions of heating and cooling end uses to residential energy consumption are 53 and 4.5 percent of total, respectively. Passive solar heating in particular is thus worthy of our attention. Passive solar heating systems comprise distinguishable components and are affected by certain requirements. The basic components perform the functions of collection, absorption, storage, distribution, and control (Houghton et. al., 1996; Steven Winter Associates, 1981). The function and composition of these components is indicated in the following table.

Table 6 The function, action, and typical composition of passive solar heating system components (from Houghton et. al., 1996; Steven Winter Associates, 1981; Martin , 1997).

Component Function	*Action*	*Typical Composition*
Collection	Admits solar radiation	Vertical or sloped glazed building opening
Absorption	Converts sunlight to heat	Dark-coloured building opening
Storage	Retains heat (or cold) for later release	High-mass materials: brick; masonry; concrete; water
Distribution	Delivers heat (or cold) to living spaces	Radiation and convection in an open-plan design
Control	Regulates heat loss (or gain) in to and out of the passive system	Optimization of system elements: proper sizing of system elements; adequate shading; correct organization of components; possibly solar reflectors and movable insulation

Three types of passive solar heating systems have been designed: direct gain; indirect; and isolated:

> For direct gain sunlight enters the heated space, is converted to heat at absorbing surfaces, and is dispersed throughout the space and to the various enclosing surfaces and room contents.
>
> For indirect category systems, sunlight is absorbed and stored by a mass interposed between the glazing and the conditioned space. The conditioned space is partially enclosed and bounded by the thermal storage mass, so a strong natural (and uncontrolled) thermal coupling is achieved. (Morehouse, 1997)
>
> The isolated category is an indirect system, except that there is a distinct thermal separation (by means of either insulation or physical separation) between the thermal storage and the heated space (Morehouse, 1997).

Examples of these three categories are shown in the following figures. Figure 20 describes a direct gain system. Figures 21, 22, and 23 describe the thermal storage wall, the attached sunspace, and the thermal storage roof, all examples of indirect passive systems. Figure 24 describes the convective loop, an example of an isolated system.

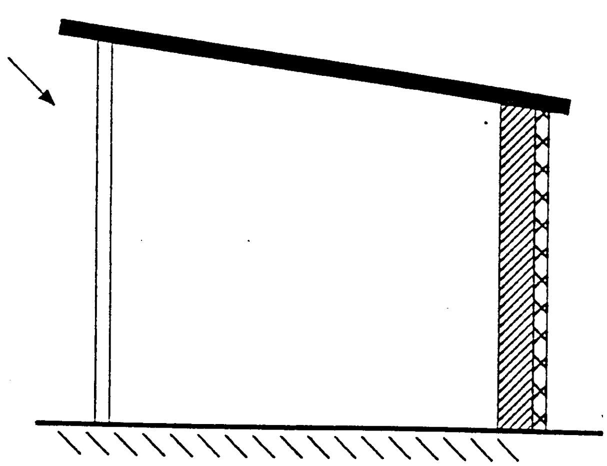


Figure 20 Direct gain (from Morehouse, 1997).

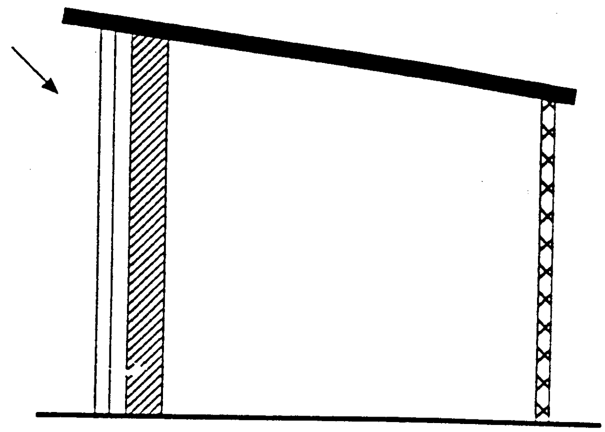


Figure 21 Thermal storage wall (from Morehouse, 1997).

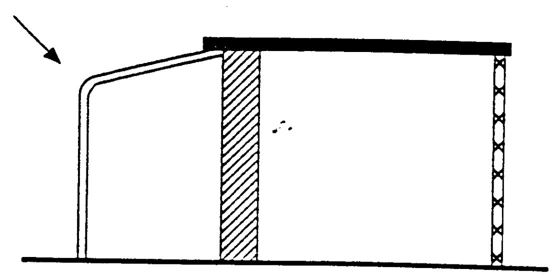


Figure 22 Attached sunspace (from Morehouse, 1997).

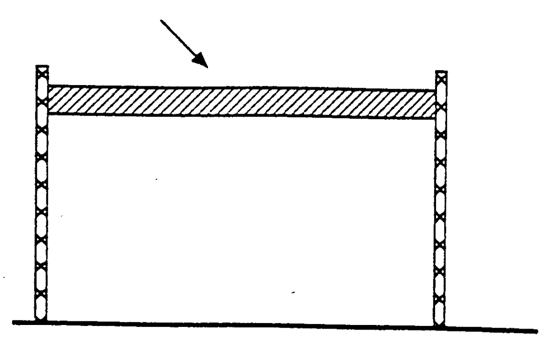


Figure 23 Thermal storage roof (from Morehouse, 1997).

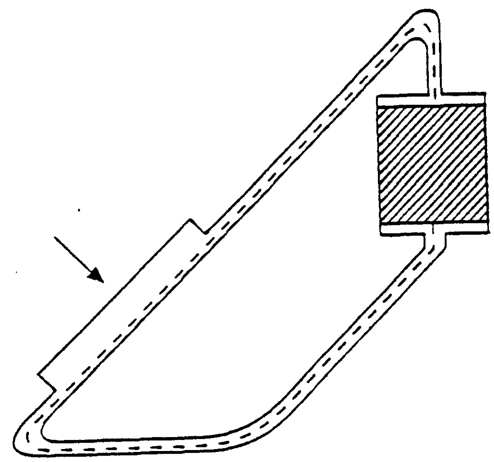


Figure 24 Convective loop (from Morehouse, 1997).

There are four types of requirements for passive solar systems, those related to site planning, shading, building configuration, and the energy-conserving characteristics of the structure. Site planning is the "organization of the external physical environment to accommodate human behaviour" (Lynch and Hack, 1984). It is the subject of much professional and academic thought beyond the simple concern of building energy use. However, here we are most interested in the specific dimension of the science (or art) that is important to passive solar systems: orientation. "Buildings should be oriented and designed to take advantage of the low winter sun, while incorporating features to shade the solar gain in the summer when the sun is high in the sky" (Houghton et. al., 1996). An appropriate relationship is shown in the following figure.

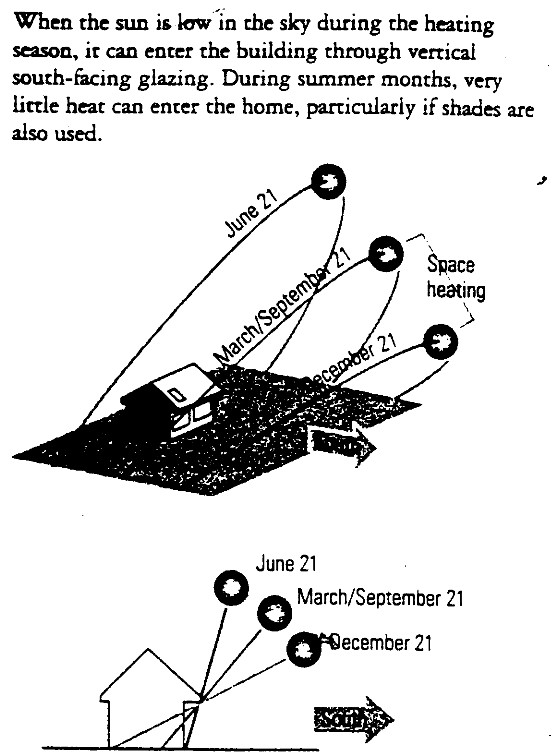


Figure 25 The relationship of a (northern hemisphere) passive solar building to the seasonal and diurnal paths of the sun (from Houghton et. al., 1996).

Appropriate shading is another requirement of passive solar systems, and is inter-related with the orientation requirement. In winter, "unwanted shading from structures to the south of the building should be avoided" (Houghton et. al., 1996). This is effected by maintaining adequate distances between adjacent buildings to permit solar gain (afforded by proper orientation). Appropriate minimum overshading is shown in the Figure 26 section drawing. The plan view of this development also demonstrates appropriate building orientations.

In general, taking advantage of the winter sun requires as much "solar access" as possible (Martin, 1997). This generates a wide variety of additional concerns, for example in relation to community layout *(ibid.)* and "sun rights" (Sherwood, 1997). In community

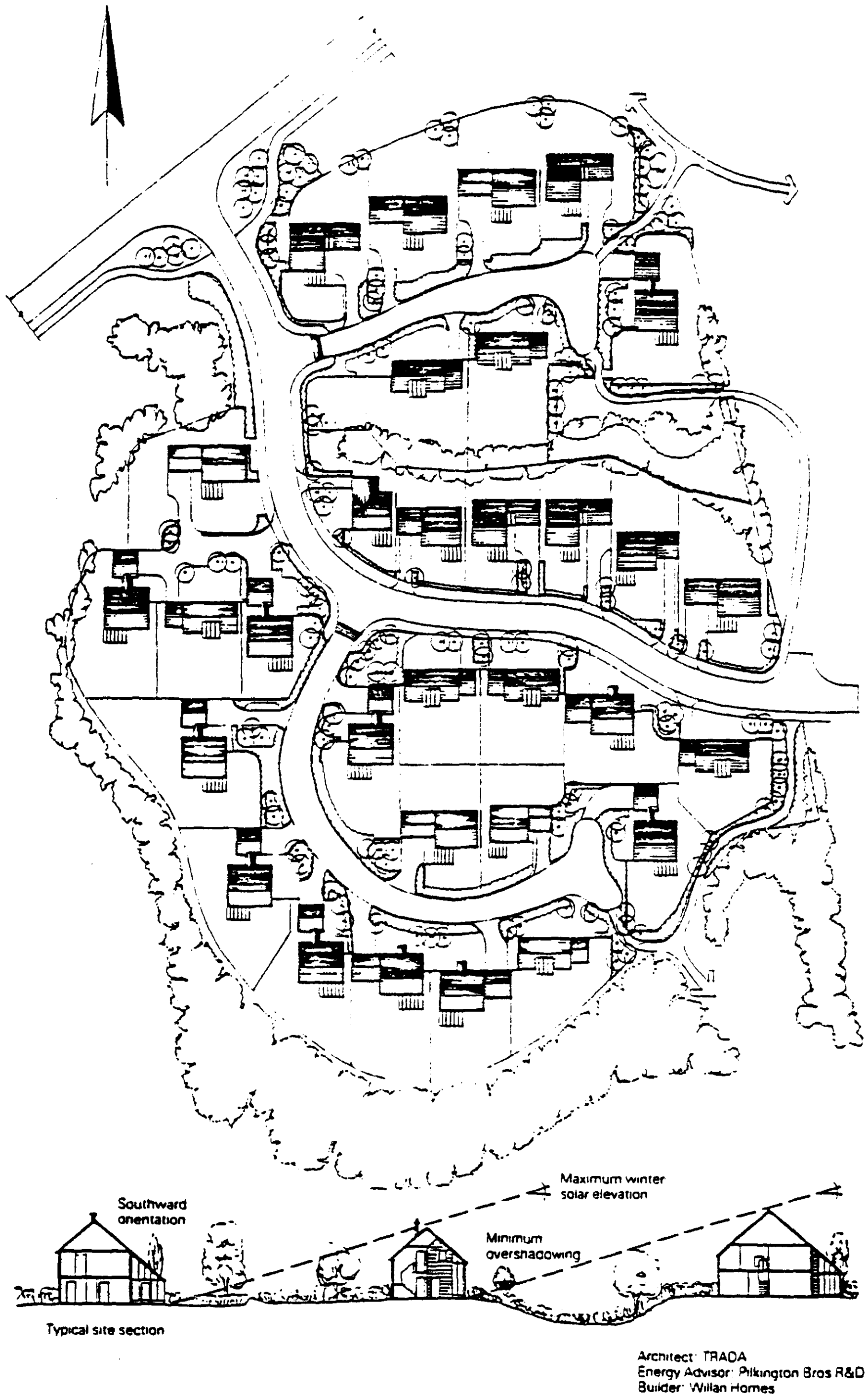


Figure 26 An example of appropriate building orientation (plan view) and appropriate minimum overshading (elevation view) (source: Pitts and Willoughby, 1992).

layout, east-west oriented streets provide the best solar access, particularly on the south side of the street where it is not likely to compete with building entrances. The definition of "sun rights" by a municipality or other public authority ensures access to solar radiation in places where these resources could easily be impinged upon by adjacent developments, for example.

A different shading concern dominates in the summer: avoidance of overheating (Houghton et. al., 1996). This can be achieved through properly-sized architectural elements such as eaves and balconies. A "rule of thumb" for south-facing windows is provided in Figure 27. One successful example of solar shading on a southern building face is shown in Figure 28.

Another requirement for effective implementation of passive solar systems is building configuration, a concern that like site planning, is driven by a large number of non-energy concerns as well. Nevertheless, recommendations can be articulated. While positioning living spaces on the south side of a building, it is advantageous to use service and circulation spaces as a "buffer" to the north. Heat-generating areas such as the kitchen are best positioned to the north to make best use of solar heating. Vestibules to external doors reduce ventilation heat loss. It is important to consider air movement within the house to enable inter-zone transfer of solar heat gains (and cross-ventilation for summer cooling). Heating and hot water systems should be placed within the insulated building shell to contain heat gains (Pitts and Willoughby, 1992).

A final requirement or consideration for the effective implementation of a passive solar system is the need for an energy-conserving structure, or the need for the facility to effectively resist outward heat flow.

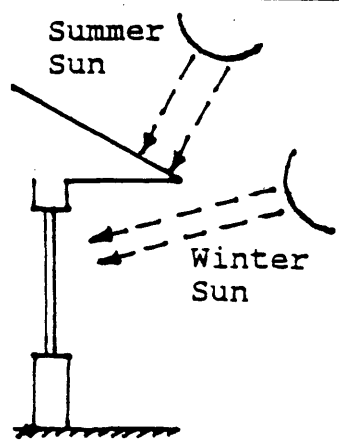
> It should be emphasized that passive solar technologies are only effective in reducing energy is they are combined with, not substituted for, standard energy conservation techniques. Any energy gains which a passive system might generate can be easily offset by the energy losses that will occur in a poorly designed and constructed building (Steven Winter Associates, 1981).

Length of the Overhang = $\frac{\text{Window Height}}{F}$

(a) Overhang Factors

North Latitude	F*
28	5.6–11.1
32	4.0–6.3
36	3.0–4.5
40	2.5–3.4
44	2.0–2.7
48	1.7–2.2
52	1.5–1.8
56	1.3–1.5

(b) Roof Overhang Geometry



Properly sized overhangs shade out hot summer sun but allow winter sun (which is lower in the sky) to penetrate windows.

* Select a factor according to your latitude. Higher values provide complete shading at noon on June 21; lower values, until August 1.
Source: Halacy, 1984.

Figure 27 Shading "rule of thumb" for south-facing windows (from Halacy, 1984 in Morehouse, 1997).

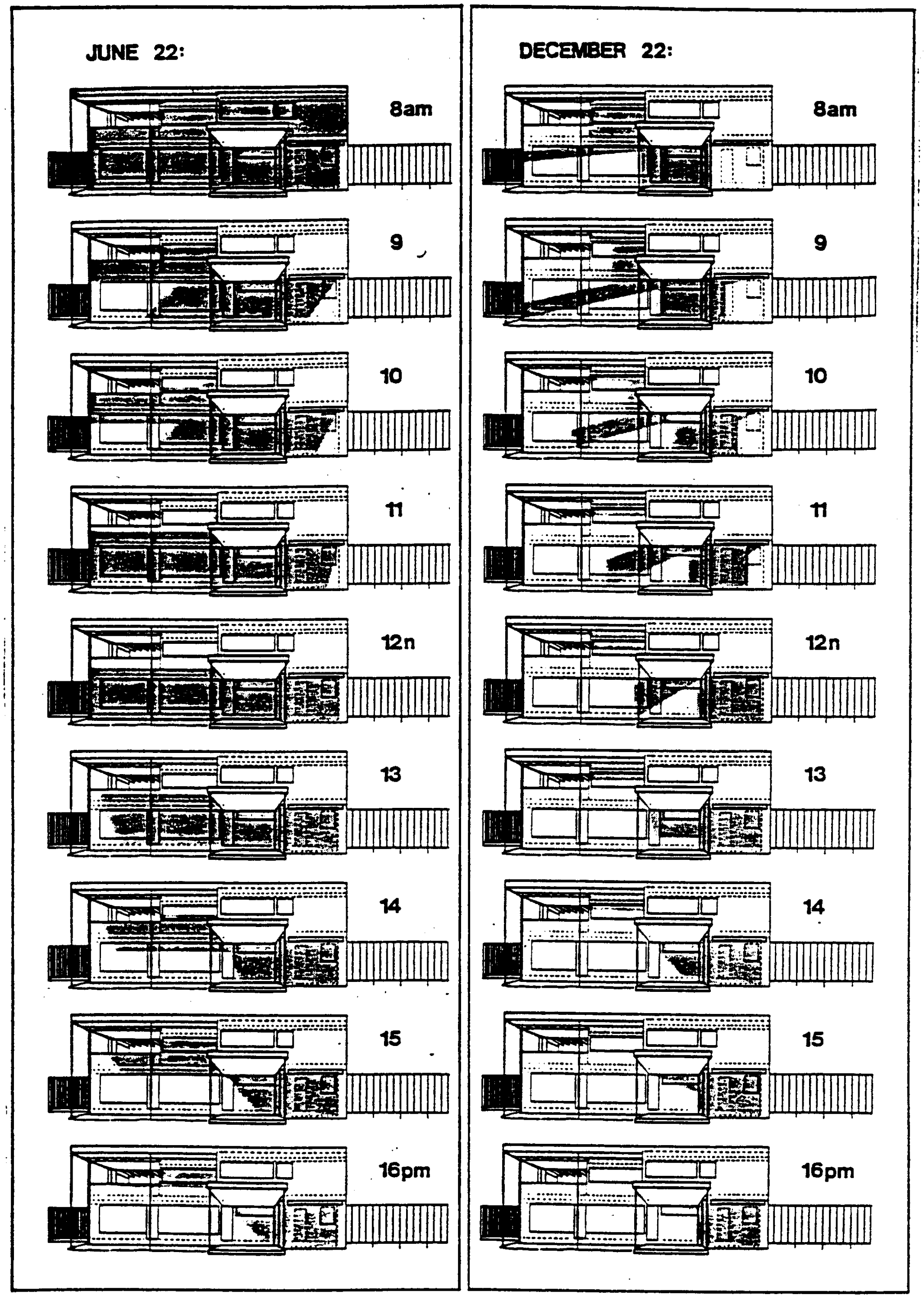


Figure 28 Analysis of window wall shading of the Gropius House (Source: Summers, 1977 in Watson, 1979).

We might even turn to *superinsulation*, which acts by containing the heat (or cold) gained through passive solar systems as well as that emitted by people, lighting, and appliances. It is a measure deemed by Rosenfeld and Hafemeister (1988) to be cost-effective on its own, even without the use of passive solar systems. In order for energy savings to be realized with superinsulation, a *continuity* requirement must be met. All elements of a facility should be well insulated in order to take advantage of a heavily insulated ceiling, for example. The components generally include: (1) heavily insulated walls and ceilings; (2) tight-fitting components; and (3) ventilation systems that recover heat from the exhaust air (Rosenfeld and Hafemeister, 1988). We might also include low-emissivity windows which allow the transmission of the visible electromagnetic spectrum while rejecting the heat-generating infrared portion.

Passive Cooling Systems

A passive solar cooling system transfers heat from a building to the environment using convection and ventilation, evaporation, radiation, or conduction. One passive cooling approach uses cool night air to reduce the temperature of a thermal storage mass. Another uses the "stack effect" to induce ventilation, as described in Figure 29.

Daylighting

Daylighting uses sunlight and skylight for the natural illumination of interior spaces. Light is admitted through building openings, and moderated using a building's architectural features or aperture controls such as blinds (Morehouse, 1997). Examples of natural lighting based on different architectural details are shown in Figure 30.

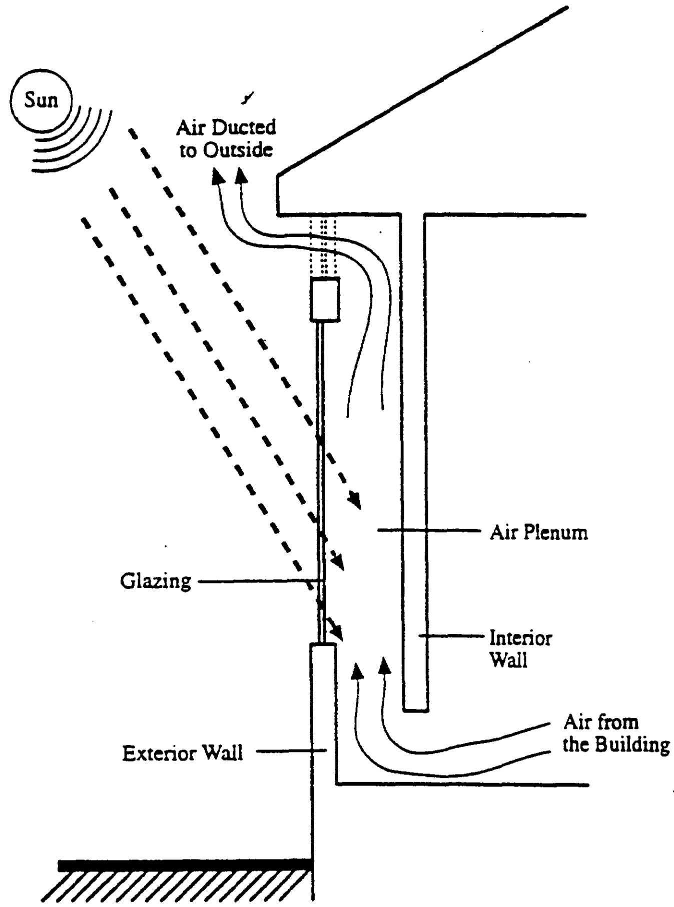


Figure 29 Use of stack effect to induce convection and ventilation (from PSDH, 1980 in Morehouse, 1997).

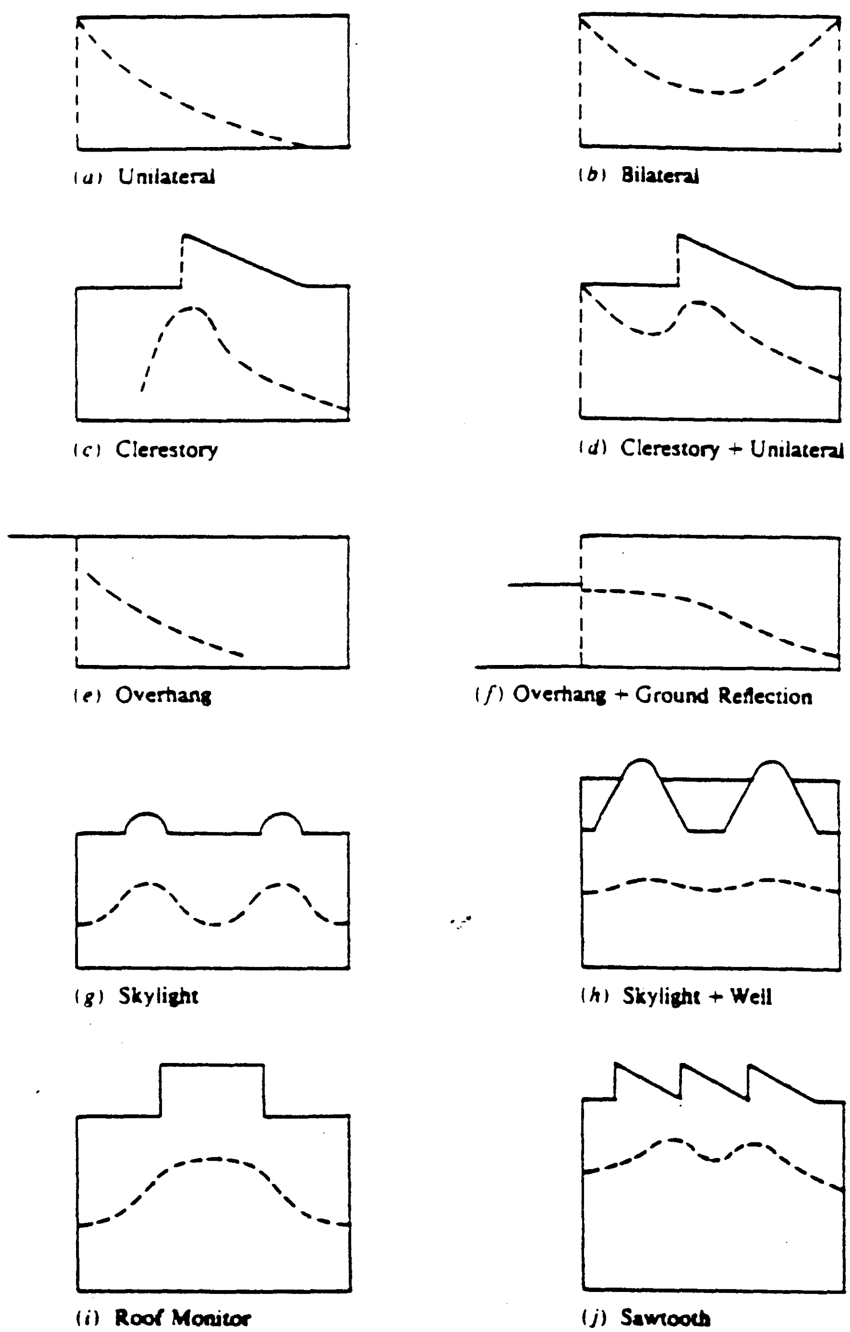


Figure 30 Natural lighting intensity based on different architectural details (source: Morehouse, 1997).

Rosenfeld and Hafemeister (1988) emphasize that means exist to reflect more sunlight into a space than would have otherwise entered, and that new systems "actuated by photocells and controlled by microprocessors dim artificial lights in proportion to available daylight." An example of this type of daylighting system is shown in Figure 31.

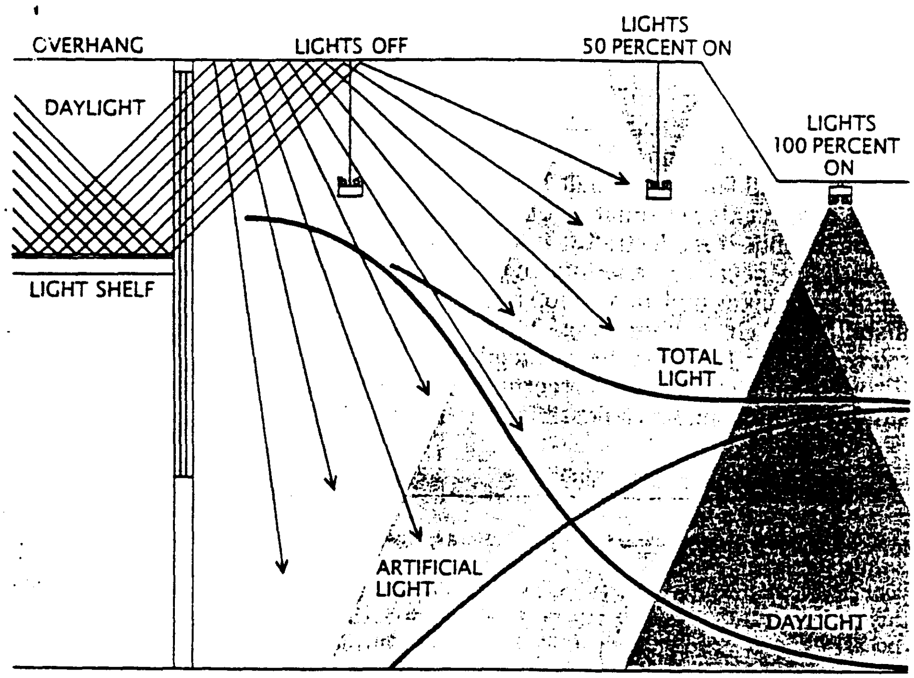


Figure 31 Daylighting (from Rosenfeld and Hafemeister, 1988).

These extensive requirements and subtle action of passive heating, cooling, and daylighting systems point to the importance of an integrated approach to their implementation. Passive solar systems are certainly not component innovations that can be specified as after-thoughts. Passive solar design is in fact the opposite: it requires early commitment in a project life-cycle, informed implementation, and a great deal of holistic thinking about the operation of the facility.

B. Energy-efficient Appliances

Once we turn to analysing the diffusion of passive solar technology, it becomes clear that the configurational and design-based nature of the technology impedes its diffusion in residential buildings. There is no such problem with energy-efficient appliances. Energy-efficient appliances perform the same functions as inefficient ones -- they are perfect substitutes. They differ only in the precise mechanism by which they function and sometimes, the relative magnitude of their initial and operating costs. As discussed earlier in the chapter, energy-efficient appliances include refrigerators and freezers, cooking appliances, clothes washers, clothes dryers, dishwashers, and others. Some specific and timely energy-efficient appliance-related innovations include the induction cooktop, cold-water laundry detergents, the halogen cooktop, the horizontal-axis clothes washer, and the heat-pump water heater (HPWH).

Even within this specific end use, the variety in types of innovation is evident. For example, cold-water detergents would be introduced as consumer products while washing machines as durable goods. Although the HPWH is also a durable good, it is one that is likely to form part of the infrastructure of the house and concomitantly may fail to command the attention or even the recognition of the householder. As a result, its specification may rest in greater part with the developer, architect, or engineer in the design development phase. In this section we specifically discuss one such energy-efficient appliance, the horizontal-axis clothes washer.

Horizontal-axis Clothes Washer

The function of the horizontal-axis clothes washer and its relation to the rest of the system remains unchanged from traditional vertical-axis washers.

The change to a horizontal-axis from a vertical-axis (which command 96 percent of the North American market) machine reduces energy use in clothes washing by *50 to 70 percent* (Houghton et. al., 1996). In a horizontal-axis machine, the clothes are alternately plunged and removed from into a shallow pool of water at the bottom of a drum rotating on a horizontal axis. By contrast, in a vertical machine, the clothes are agitated in a vertical drum which must be filled with water. The horizontal axis machine thus uses far less water and a correspondingly lesser amount of energy. The significance of this saving is highlighted by the fact that in clothes washing, 85 to 90 percent of the energy consumption goes to water heating. The horizontal and vertical axis machines are shown in Figures 32 and 33, respectively.

Horizontal-axis washers clean clothes by plunging them in water and detergent. Machines can be front or top loading.

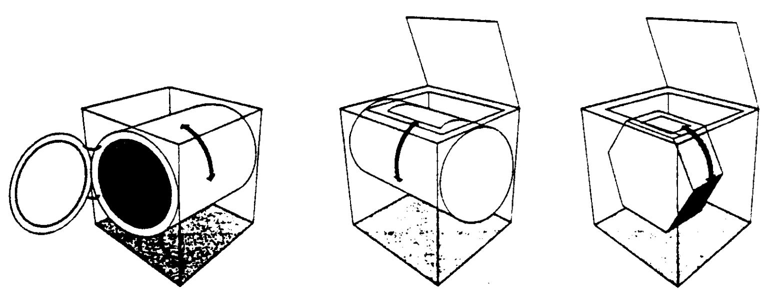


Figure 32 Horizontal-axis clothes washer (from George et. al., 1996).

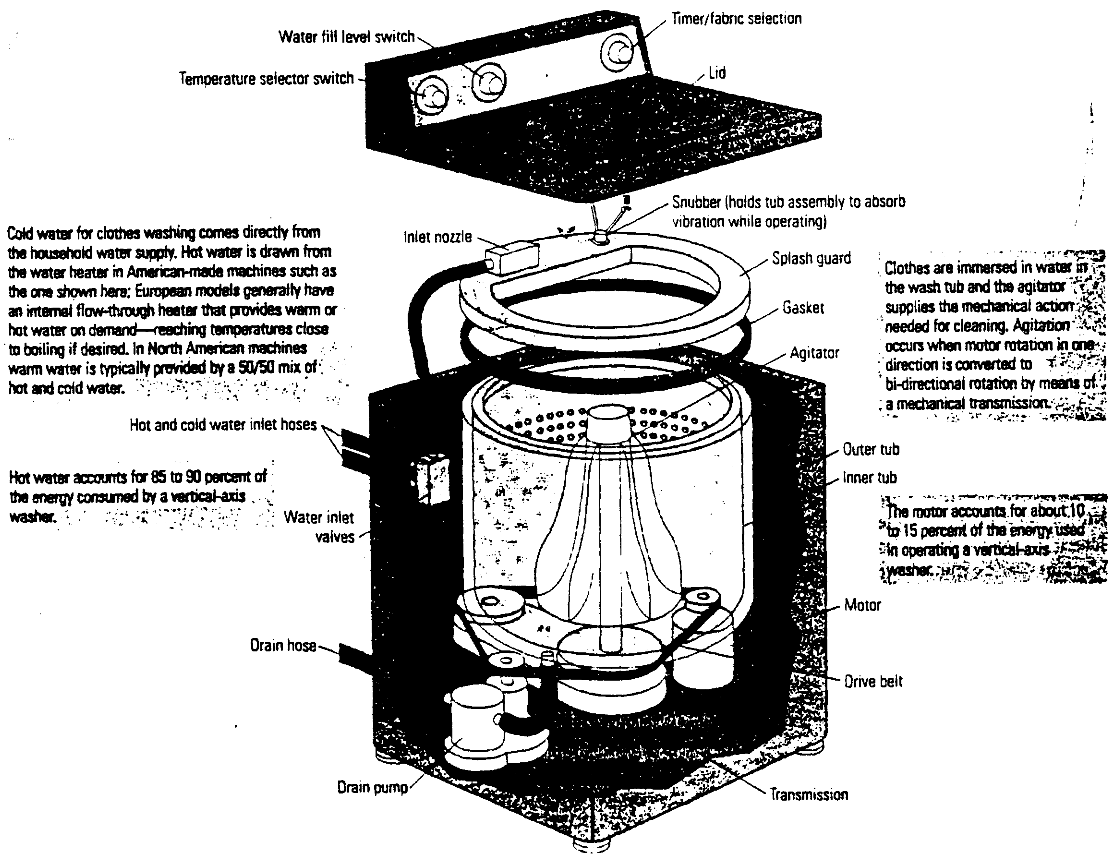


Figure 33 Vertical-axis clothes washer (from George et. al., 1996).

C. Urban Trees and White Roofs

One innovation based in a modification to urban, rather than building, systems is the widespread introduction of trees in urban environments. Akira Kinoshita, of EPDC Engineering Research, Tokyo, has related green cover ratio to a reduction in urban temperature (as well as increased pollutant absorption), quantified in Figure 34.

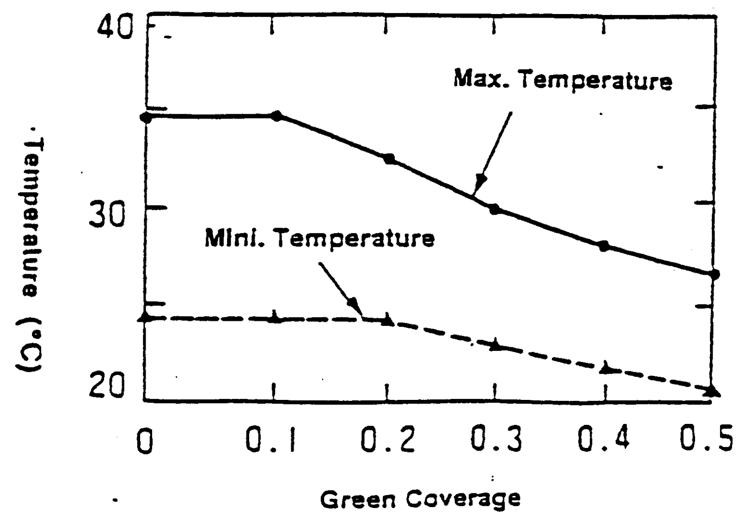


Figure 34 The relationship between green cover and urban temperature (from Kinoshita, 1996).

On the same topic, Arthur Rosenfeld et. al. (1995) at the Lawrence Berkeley Laboratory "Cool Communities Program" have studied the "building- and city-scale effects of the urban surface on energy use and climate." "At the building scale, dark roofs are heated by the summer sun and thus raise the summertime cooling demands of buildings. Collectively, the dark surfaces and reduced vegetation warm the summer air over urban areas, leading to the creation of the summer urban 'heat island'" (Rosenfeld et. al., 1995).

According to the authors, 5-10 percent of urban peak electricity demand[2] is attributable to this urban air temperature increase at an annual cost of billions of dollars. The heat island effect can be reversed by increasing urban surface albedo[3] and widespread tree planting. Trees in particular reduce electricity use at about 1 percent of the cost of installing new supply and avoided air conditioning equipment (Rosenfeld et. al., 1995).

CONCLUSION

This chapter reviewed building systems and put form to the conserved energy supply curves shown in Section 1.1, "Motivations for Research." Passive solar systems, the horizontal-axis clothes washer, and urban trees and white roofs were described in detail. This thesis now turns from background -- motivations, methodology, energy efficiency trends, technology models, and efficiency technologies -- to analysis. Of first concern is the natural propensity of a particular efficiency technology to diffuse into the community of potential users. The next item is the effect of regulation where I assess the treatment of technology under federal appliance efficiency standards. These two pieces of analysis are then used as building blocks in an inductive characterization of the technological dynamic of the residential building sector.

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[2]The 5-10 percent figure is based on a study of six warm American cities, Los Angeles, CA, Washington, DC, Phoenix, AZ, Tuscon, AZ, and Colorado Springs, CO, reported in Akbari et. al., 1992.
[3]Lynch and Hack (1984) provide the following explication: "*Albedo* is a surface characteristic, defined as that fraction of the total radiant energy of a given wavelength incident on a surface that is reflected back instead of being absorbed. A surface with an albedo of 1.0 is a perfect mirror, reflecting back everything that shines on it, without itself receiving any heat or light. A surface whose albedo is zero is a perfect matte black surface, reflecting nothing and soaking up all the radiation that falls on it. These same properties hold when the flow of radiation reverses: a hot surface of low albedo radiates rapidly. Albedo may therefore be imagined as the relative permeability of a surface to radiant energy flowing in either direction. High albedos resist this flow, and low albedos facilitate it."

REFERENCES

AKBARI, H., S. Davis, S. Dorsano, J. Huang, and S. Winnett, editors, 1992. *Cooling Our Communities: A Guidebook on Tree Planting and Light-colored Surfacing*. U.S. Environmental Protection Agency Office of Policy Analysis, referenced in Rosenfeld et. al., 1995.

AUDIN, Lindsay et. al., 1994. *E Source Technology Atlas Series Volume 1: Lighting*, E Source, Inc., Boulder, CO.

BARNETT, Diana Lopez with William D. Browning, 1995. *A Primer on Sustainable Building*. Rocky Mountain Institute Green Development Services, Snowmass, CO.

CARLESTAM, Gösta, Tommy Månsson, Ingvar Henriksson, and Claes Reuterskiöld, 1979. "Energy Management and Land Use Planning," from Swedish Council for Building Research, *Programme for Energy-related Research, Development, and Demonstration EFUD 78*, Stockholm.

CHING, Francis D.K. with Cassandra Adams, 1991. Building Construction Illustrated (Second Edition). Van Nostrand Reinhold, New York,

DE NEUFVILLE, 1990. *Applied Systems Analysis: Engineering Planning and Technology Management*. McGraw-Hill, New York, 470 pp.

GELLINGS, Clark W. and John H. Chamberlin, 1993. *Demand-Side Management: Concepts and Methods* (Second Edition), The Fairmont Press, Lilburn, GA, 451 pp.

GEORGE, Karen et. al., 1996. *E Source Technology Atlas Series Volume 5: Residential Appliances*, E Source, Inc., Boulder, CO.

HALACY, D. S., 1984. *Home Energy*, Rodale Press, Emmaus, PA, referenced in Morehouse, 1997.

HENDERSON, Rebecca M. and Kim B. Clark, 1990. "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," *Administrative Science Quarterly*, Vol. 35, pp. 9-30.

HIRST, Eric, Jeanne Clinton, Howard Geller, and Walter Croner, 1986. "Chapter 9: Government Conservation Programs." In: O'Hara, F.M. Jr., Ed. *Energy Efficiency in Buildings: Progress and Promise*. American Council for an Energy-Efficient Economy, Washington, DC, 328 pp.

HOUGHTON, David et. al., 1996. *E Source Technology Atlas Series Volume 3: Space Heating*, E Source, Inc., Boulder, CO.

KELLY, Burnham, 1959. *Design and the Production of Houses*. McGraw-Hill, New York.

KINOSHITA, Akira (EPDC Engineering Research, Tokyo), 10 June, 1996. "Total Energy System Integrated with Urban Planning," paper prepared for United Nations Habitat II, Settlement Infrastructure and Environment Program, Symposium on Energy, Istanbul.

LYNCH, Kevin and Gary Hack, 1984. *Site Planning* (Third Edition), MIT Press, Cambridge, MA.

MARTIN, Thomas E (Principal, Martin Associates Architects, Toronto, Ontario), July, 1997. Personal Communication.

MERRITT, Frederick S. and James Ambrose, 1990. *Building Engineering and Systems Design* (Second Edition). Van Nostrand Reinhold, New York.

MOREHOUSE, Jeffrey H., 1997. "Passive Solar Heating, Cooling, and Daylighting," in Frank Kreith and Ronald E. West, editors, 1997. *CRC Handbook of Energy Efficiency*, CRC Press, New York.

MURDOCH, J. B., 1985. *Illumination Engineering -- From Edison's Lamp to the Laser*, Macmillan, New York.

NAHB (National Association of Home Builders of the United States), 1974. The Builders Guide to Energy Conservation. NAHB, Washington, D.C.

NADEL, Steven, Dick Bourne, Michael Shepard, Leo Rainer, and Loretta Smith, February, 1993. *Emerging Technologies to Improve Energy Efficiency in the Residential & Commercial Sectors*. American Council for an Energy-Efficient Economy, Washington, D.C.

OWENS, Susan, 1984. "Spatial Structure and Energy Demand," in Cope, David R., Peter Hills, and Peter James, editors, *Energy Policy and Land-use Planning: An International Perspective*. Pergammon Press, New York.

PALMER, Mickey, 1981. *The Architect's Guide to Facility Programming*, American Institute of Architects (AIA), Washington, D.C.

PELLISH, David M., 1990. "Buildings in the Next Century," in Jefferson W. Tester, David O. Wood, and Nancy A. Ferrari, editors. *Energy and the Environment in the 21st Century*, MIT Press, Cambridge, MA.

PITTS, Geoffrey and John Willoughby, 1992. "A design guide to energy efficient housing," in Roaf, Susan and Mary Hancock, Eds., *Energy Efficient Building: A Design Guide*. Blackwell Scientific Publications, Oxford.

ROSENFELD, Arthur H., 1990. "Energy-Efficient Buildings in a Warming World," in Jefferson W. Tester, David O. Wood, and Nancy A. Ferrari, editors. *Energy and the Environment in the 21st Century*, MIT Press, Cambridge, MA.

ROSENFELD, Arthur H. and David Hafemeister, 1988. "Energy-efficient Buildings," *Scientific American* Vol. 258, No. 4 (April), pp. 78-85.

ROSENFELD, Arthur H., Hashem Akbari, Allan Chen, and Haider Taha, 28 August 1995. "The Cool Communities Program in Brief," LBL Center for Building Science information brief. Energy and Environment Division, Lawrence Berkeley Laboratory, Berkeley, CA.

SHEPARD, Michael et. al., 1995. *E Source Technology Atlas Series Volume 2: Commercial Space Cooling and Air Handling*, E Source, Inc., Boulder, CO.

SHERWOOD, Larry (Executive Director, American Solar Energy Society, Boulder, CO), July, 1997. Personal Communication.

SLAUGHTER, Sarah, 1997. *Innovation in Construction*, class taught in the Department of Civil Engineering at the Massachusetts Institute of Technology, Cambridge, MA.

STEADMAN, Philip, 1980. *Configurations of land-uses, transport networks and their relation to energy use*. Centre for Configurational Studies, Open University, Milton Keynes, referenced in Owens, 1984.

STEVEN WINTER ASSOCIATES, INC. (Building Systems Consultants, NY, NY), 1981. *Passive Solar Construction Handbook*, prepared for Southern Solar Energy Center, Atlanta, GA and United States Department of Energy, Washington, DC.

TURRENT, D., J. Doggart and R. Ferraro, 1980. *Passive Solar Housing in the UK*. ECD Partnership, London, referenced in Pitts and Willoughby, 1992.

U.S. OTA (Office of Technology Assessment), 1982. *Energy Efficiency of Buildings in Cities*. U.S. OTA, Washington, D.C.

WATSON, Donald, Ed., 1979. *Energy Conservation through Building Design*. McGraw Hill, New York.

6

Passive Solar Technology Case Study

Introduction

In this chapter I analyse a specific configurational technology using the models of innovation and diffusion described in Chapter 4. This analysis is a building block in the central, inductive argument of the thesis: the residential building sector suffers from technological constipation in the dimension of energy efficiency. The inherent nature of a number of important residential energy efficiency technologies and the way in which they interact with their environment -- the housing market, for example -- cause these technologies not to diffuse freely and rapidly, but rather to stagnate.

In this chapter I examine the special characteristics of passive solar systems in light of innovation and diffusion models. Passive solar design is a new referent for an old concept. By carefully configuring a building and establishing an appropriate relationship to the diurnal and seasonal paths of the sun, energy use for heat and light can be drastically reduced. David et. al. (1996) reckon that properly-designed solar gain and storage and a well-insulated shell can cut heating energy by more than 75 percent, and in some cases, completely eliminate it. Even measures as simple as proper orientation with no explicit plan for capturing and storing solar energy can produce savings of 10-20 percent. Yet the widespread adoption of passive solar systems and design principles remains sparse at best.

The current figure for the number of houses incorporating passive solar principles, cited for example by E-Source and the American Solar Energy Society (ASES), is 250 thousand units out of a total housing stock of over 100 million units. Additions to the stock currently run about 10 thousand passive solar homes per year according to Larry Sherwood, the Executive Director for ASES. Surely this is less than is to be expected based on the technological feasibility and economics of the innovation. This mystery can be largely explained using the models of innovation and diffusion described earlier in the thesis. The use of passive solar heating systems requires a fundamentally different mode of thinking of most of the participants in the design-build process. Passive solar systems define a different *technological paradigm*, incorporating a different set of "technological alternatives" and "notional future developments," according to Dosi's (1981) characterization of technology. When this view is coupled with the recognition that passive solar design can really only diffuse in an evolutionary manner, evolving locally as it is adopted, it becomes clear how such a brilliant innovation can limp along at such a lame pace. Passive solar systems define a new technological paradigm, and this redifinition must occur and re-occur virtually every time the technology is adopted, making for a laborious diffusion process. This case study starts with an overview of the origins and historical diffusion of passive solar systems. It then describes the applicability of the innovation from both technical and cost perspectives. The innovation is then characterized using the models of technological innovation described earlier, and the implications of this characterization for diffusion are discussed. This is the heart of the thesis. When the "inherent peculiarities" of passive solar systems are viewed alongside "the organization of he industry and its methods of production" (Nelkin's, 1971), a plausible interpretation of the diffusion of passive solar systems emerges. In Chapter 7, I go on to discuss the effects on technology of a specific instance of regulation.

6.1 Historical Diffusion

Passive solar systems are not a recent design innovation but rather, a technology or set of principles that have been developed and nurtured over time. Tracking the use of passive solar technology is difficult, however. Data are difficult to define. Passive solar systems are not embodied in a product but rather in the relationship between certain elements in a building. There is thus a definitional issue in figuring what can reasonably be said to be the use of a passive solar system. No special components can be tracked by sale, and the main responsibility for implementing each system is spread between a large, diffuse group of designers, builders, and owners.

Yet estimates exist: 250 thousand passive solar homes in the Unites States is the figure that is cited in virtually all recent references on the topic. Larry Sherwood (1997) was able to translate that figure into a rough set of year-by-year data based on his intuition and long-time interest in the technology. It looks something like the following plot, although he notes that "these are not +/- 1 percent figures."

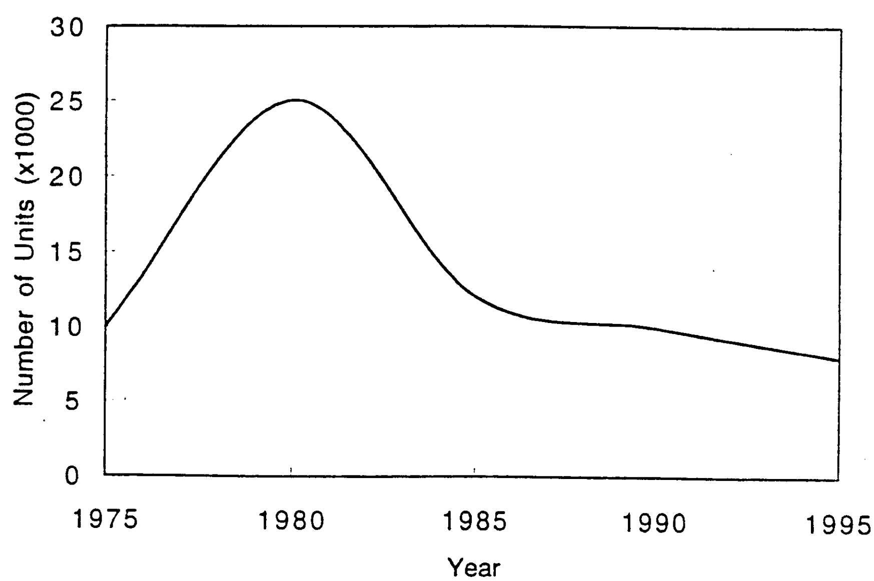

Figure 35 Approximate number of passive solar homes added to the U.S. stock on a year-by-year basis, late 1970s to the present (source Sherwood, 1997).

The data for these figures were collected from three main sources: tax credit information from the late 1970s and early 1980s; an extrapolation of certain states' relatively detailed housing surveys; and market surveys from certain utilities. As evidenced by the figures, passive solar technology enjoyed a peak in the late 1970s and early 1980s but has since tapered off.

6.2 Technical and Economic Applicability

The range of situations in which passive solar technology is potentially applicable is constrained by technical and economic factors. From a technical perspective, the following maps are instructive.

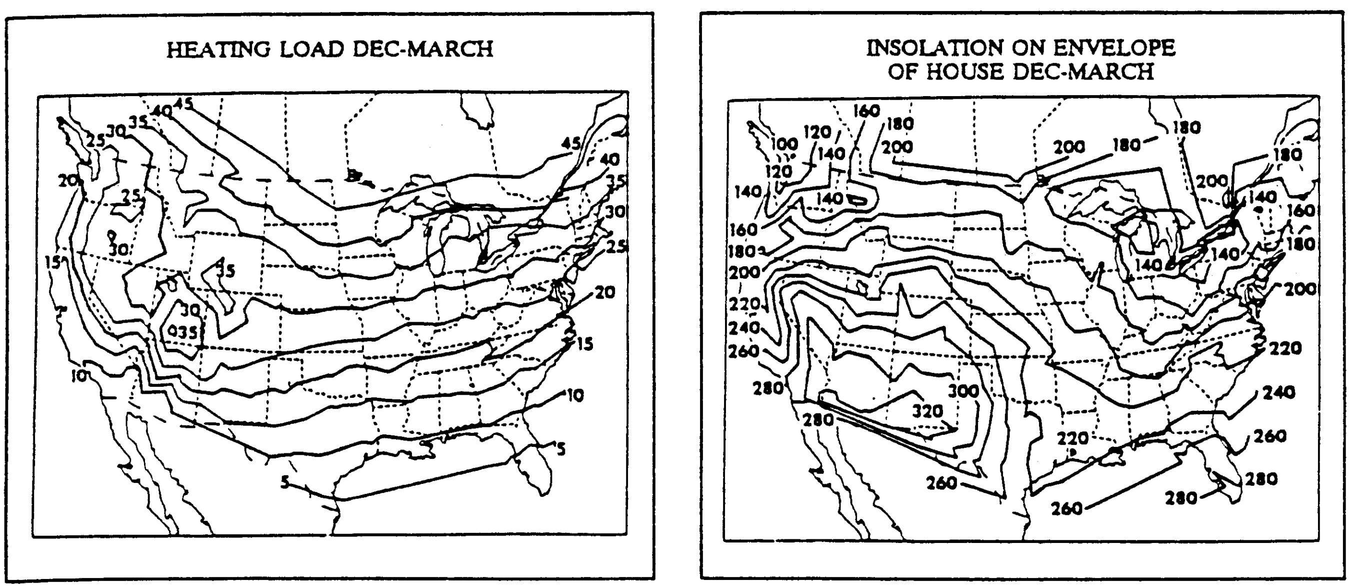

Figure 36 The juxtaposition of December - March heating loads with insolation on a 1200 ft^2 house envelope over the same period (Units: MMBtu) (source: Neeper and McFarland, 1982 in Pellish, 1990).

Even in the northernmost reaches of the country, winter insolation on the building envelope is at least four times the required heating load over the same period[1]. Simultaneously, "more than 20 times the light required to light building interiors is available from natural sunlight" (Pellish, 1990). From a technical perspective, the opportunities for the use of solar energy are almost limitless, particularly in light of emerging technologies such as "smart windows," "controllable membrane" building envelopes, fibre optics, etc.[2]

The economics of the technology are equally as compelling:

> Effective passive solar houses can be constructed for a marginal cost ranging from $1,000 to $5,000 per house, with a cost of saved energy of about $1 to $10 per million Btu. In some cases, good solar design costs no more than conventional construction, if the cost of added insulation and better windows allows HVAC equipment to be downsized or eliminated. (Houghton et. al., 1996)

The additional costs are incurred in higher design expenses, extra or unusual materials, components, or construction techniques (Houghton et. al., 1996). Both ASES and Lawrence Berkeley Laboratories have made cost estimates for implementation. These are presented in Table 7.

Table 7 A cost summary of residential energy provision by different means.

Energy Source	*Cost ($/million Btu)*	*Reference Source*
natural gas	6	Houghton et. al., 1996
electricity	25	*ibid.*
conserved energy from passive solar technology	5-10 (over a 30-year system lifetime)	ASES. 1992
conserved energy from passive solar technology installed in gas homes	5.25	LBL, 1986 in Houghton et. al., 1996
conserved energy from passive solar technology installed in electric homes	8.50	*ibid.*

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[1]*Insolation* is defined as "exposure to the sun's rays .." (Brown, 1993).

[2]A number of these technologies to make taking advantage of insolation on the building envelope even easier are described in Pellish, 1990.

The essential economic trade-off occurs between the aggregated saved energy (performance) and the initial investment[3]. Performance is computed by subtracting a passive solar facility's energy costs from the energy costs of a similar non-passive solar facility. The result in net annual energy saved (Morehouse, 1997). The convention is to define a "solar add-on cost." However,

> this is a difficult definition in the case of most passive solar designs because the building is significantly altered compared to typical construction. In the case of a one-to-one replacement of one wall for another, the methodology is relatively straightforward. However, in other cases it becomes more complex (and more arbitrary) and involves assumptions and simulations concerning the typical construction building. (Morehouse, 1997)

In reality, the applicability of passive solar systems is constrained by other factors as well -- otherwise the technology would be widely used. Indeed, our main question is why passive solar systems are not more prevalent given their excellent technical and economic feasibility. This question is explored in the next two sections, which analyze the technology from the viewpoints of models of innovation and diffusion.

6.3 The Characterization of Passive Solar Systems by Diffusion Model

In the case of passive solar technology, little debate is required in deciding in what manner the technology is likely to diffuse. It is clearly evolutionary. There is no central source for the innovation and there is no discernible, unchanging product. The diffusion of passive solar systems thus cannot be interpreted using the classical model. The evolutionary model assumes that the innovative aspects of diffusion cannot be differentiated -- the technology changes and is modified locally as it diffuses. This makes a great deal of

[3]Morehouse, 1997 notes that it is appropriate to view both performance and cost as life-cycle costs (initial investment + operations and maintenance) rather than simply initial investment.

sense. Passive solar systems are use-specific. Each application must be sensitive to the insolation pattern, microclimate, and special characteristics of a particular site. Each application also depends on the particular function or functions of the facility in question.

We can thus turn to the forces that we might expect to drive the diffusion process according to the Cainarca et. al. (1989) model: the degree of appropriability; the potential for cross-fertilization between suppliers and users; technological complementarities; and the expected profitability and cost of the innovation.

Three out of four of these determinants are particularly interesting. The potential for cross-fertilization between suppliers and users would likely have a relatively neutral effect on the diffusion of passive solar systems. Although as users homeowners would have day-to-day contact with the operation of the passive system, they may not be apt to provide constructive feedback to the supplier as once it is installed because of the permanence of the system: it is unlikely to be modified except by renovation. Consequently, we focus on the other variables, profitability, appropriability, and technological complementarities.

The demonstrated profitability of the innovation suggest that diffusion should have been very rapid. The cost of conserved energy was discussed in the previous section -- it is on the whole cheaper than most supply options. David et. al. (1996) cite the example of Neuffer Construction, based in Reno, Nevada, which offers several passive solar homes, one of which is available at no additional cost. In fact, the profitability of passive solar measures in large part is the motivation for this inquiry. Why, given such positive economics, has widespread diffusion not occurred? The economics of the technology should be expected to act as a strong positive force in the diffusion of the technology. For hindrances, we must turn to the other factors.

In the evolutionary mode of diffusion, an innovation's interaction with technological complementarities is of critical importance. Passive solar design is a relatively autonomous technology, with the important exception of the treatment of solar access by community layout. Adequate solar access is a key requirement for the implementation of passive solar systems. On large estates, this is generally a problem involving the relationship of the facility to a site's natural elements. But in tight developments and urban areas, community layout, particularly street orientation, becomes critically important. Martin (1997) notes that in tight developments, it is virtually impossible to implement passive solar design on North-South streets. Designs for relatively dense communities that by nature of innovative street patterns and lot shapes allow for passive solar design do exist, such as that shown in Section 5.3, Figure 26. However, the implementation of such plans is dependent on a set of actors often altogether different from those who make the building programming and design decisions.

Programming and design decisions are made at the project level. The actors are developers, architects, engineers, contractors, owners. Except in the case of certain large greenfield developments, the street layout, the delimitation of lots, and the provision of local infrastructure are usually existing constraints, the form of which is determined by local planning and public works authorities. The implementation of passive solar systems depends on a technological complementarity in appropriate community layout. Because this complementarity is under the control of a different set of actors who have little to gain from a reduction in individual units' heating costs, it should be expected to act as a hindrance to the diffusion of passive solar systems. Conversely, if a community's public authorities do embrace the facilitation of passive solar design, as some have, this should be expected to be correlated with the presence of passive solar homes. Sherwood (1997) notes that the cities of Albuquerque, NM and Davis, CA and the states of Oregon and Connecticut encourage, but do not require passive solar community layout. Indeed, we should expect a greater penetration of passive solar homes in these areas. In the same vein, the definition of "sun rights," or a means for resolving the potential impingement on solar access by one facility on another should be expected to encourage the diffusion of passive solar design.

Passive solar systems score low on another factor that drives diffusion, the degree of appropriability of the innovation. Cainarca et. al. (1989) postulate a "fundamental complementarity between the diffusion pattern (and the diffusion speed) of the different technological solutions stemming from the new paradigm and the ability of firms to wholly exploit the potential of these solutions." Innovations whose benefits are hard to capture are inherently less likely to be widely accepted.

In order to analyse the appropriability of passive solar technology, we turn to the work of David Teece of the University of California, Berkeley. Teece (1988) has developed a framework with which to analyse the distribution of profits from an individual innovation. A key element in his framework is the "appropriability regime," or "the environmental factors, excluding firm and market structure, that govern an innovator's ability to capture the profits generated by an innovation" (Teece, 1988). We can use his framework to look at the appropriability of the benefits from passive solar design, which we can then discuss in terms of its facilitation or hindrance of the technology's diffusion.

There are two dimensions to the regime: "the nature of the technology and the efficacy of the legal mechanisms of protection" (Teece, 1988). Along the "nature of technology" dimension, we are particularly interested in whether the knowledge involved in the development of the innovation is tacit or codified: tacit knowledge, being "by definition hard to articulate," is difficult to transfer. This characteristic should thus be expected to strengthen the appropriability regime surrounding an innovation. Codified knowledge, by contrast, is easily transmitted between parties, weakening the appropriability regime.

Along the "efficacy of legal instruments" dimension, we are interested in the effective protection afforded to an innovation, keeping in mind the possibility of reverse engineering and "inventing around," and the potentially high costs of having intellectual property infringements upheld in the legal system. Specifically, we are interested in the protection afforded patents, copyrights, and trade secrets. The origins, scope, and requirements of, and the protection afforded by, these instruments are summarized in the following table.

Table 8 Summary of the origins, scope, and requirements of, and protection afforded by, patents, copyrights, and trade secrets (source: Caldart, 1997; Hersey, 1991).

	Patent	*Trade secret*	*Copyright*
Origins in	Constitution / federal patent statutes	State (common) law	Constitution / federal copyright statute
Scope	Unlimited	Anything of commercial value	Visible expression of a creative work, but not the ideas that underlie it; "procedure," "system," "method of operation," "principle," "discovery" all excluded
Requirements	Novel; not obvious; useful; invented by applicant	Of commercial value; unknown to your competitors; not discoverable through reverse engineering	Original works of authorship fixed in any tangible means of expression
Protection afforded	17 year monopoly	Potentially forever	Life of author + 50 years; 75 years if owned by employer

Our first question should then be whether the knowledge embedded in the design of passive solar systems could be said to be tacit or codified (or codifiable). It tends towards codifiable and codified knowledge. The principles are simple enough, and, for example, were articulated in Chapter 5. There are certainly subtleties involved in implementing the technology such as specifying the proper amount of thermal storage mass, etc. Some of this knowledge probably comes through experience and professional intuition. However, there is no reason why an interested individual couldn't come to similarly educated conclusions with a moderate amount of work and investigation. Clearly, the design of passive solar systems is not an especially tacit art or science.

Neither does the current scheme of intellectual property rights in the United States offer much in the way of making passive solar technology more appropriable. The principles of passive solar design were not invented by anyone who might now apply for a patent; the principles could not be kept secret from your competitors had the originator been interested in a trade secret; and clearly it is not an original work of authorship, but rather a "system," which is explicitly excluded from copyright protection.

The sum effect is that the appropriability regime surrounding passive solar technology is altogether weak, both from the point of view of the inherent nature of the technology and the potential protection afforded by the current scheme of intellectual property rights. When this is combined with the neutral effect of potential cross-fertilization between users and suppliers and the hindrance in the form of a required technological complementarity, the net result is that the diffusion of passive solar technology is likely to be slow. The diffusion of this technology is driven by solid economics and technical feasibility, but it is simultaneously hindered by a lack of appropriability and the complementary requirement of sensitive community layout.

6.4 The Characterization of Passive Solar Systems by Innovation Model

Despite the fact that with hindsight one can easily be overconfident in interpreting a complex process such as the diffusion of a particular technology, analysing passive solar systems from the point of view of models of diffusion does build a plausible case for why the diffusion process has been weak. The additional insights available from an analysis of passive solar systems using models of innovation makes our interpretation doubly likely. Passive solar design represents a new technological paradigm (after Dosi, 1981), an architectural innovation (after Henderson and Clark, 1990), and a fundamental revision of the dominant design of residential buildings (after Abernathy and Utterback, 1978). Each of these interpretations implies firm difficulty in adapting to this innovation. Individual's problem-solving behaviour and definition of the relevant problems reflects an old architecture and technological paradigm. The technology diffuses in an *evolutionary* manner -- implementing it in a specific case is like reinventing the wheel. This combination means that not only does the innovator need to break out of the old paradigm, but so does virtually every individual or household that might be apt to adopt it. The combination of the new paradigm and the evolutionary mode of diffusion creates an evil synergy that hinders the diffusion process. It is also an architectural innovation according to the Henderson and Clark model, and a plausible case can be made that the industry has organized itself around a standard, "old" paradigm much like the firm is expected to do in Henderson and Clark's model. These additional facts suggest that despite the fact that we are dealing with a technology that we know has diffused in a lazy manner, the reasons for this are not mysterious, but are rather clear.

Our first interest in these models is definitional: how should passive solar technology be characterized? Recalling that models of technological innovation cannot be applied monolithically, we turn to the models proposed by Henderson and Clark (1990) and Dosi (1981). The others are foregone[4].

Passive solar technology fits well into Henderson and Clark's (1990) definition of architectural innovation: it leaves core concepts like glazing unchanged while redefining the way these components are linked together. The components' functions are redefined.

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[4]My reasoning for foregoing the balance of the models discussed in Chapter 3 is as follows. Passive solar technology is not well-suited to representation under the Marquis taxonomy. It is not a complex system characterized by thorough, long-range planning. It is not really a rare and unpredictable radical breakthrough. Nor is it a "nuts and bolts" innovation paced by economic factors. If pressed, we might say that passive solar retains elements of both radical and incremental innovations. However, we are better off relying on other definitions. Foster's S-curve model relates the rate of technological development to technical potential. Using this model would really be all about defining what we felt the "technical potential" of residential building systems is -- not a fun task given that the objectives of the system are so broad, variegated, and complex that they can hardly be articulated. The Abernathy and Utterback dominant design model is better for thinking about passive solar technology than the above two, but is rather more oriented to innovations that can be mass-produced. The dominant design aspect of their model is captured nicely by the Dosi model. The relationship of the "stage" of the innovation to firm (and industry) structure is captured nicely bay the Henderson and Clark model. Thus, this last model will be used only selectively, and I will focus this section of the case study on the application of Dosi and Henderson and Clark.

Glazing becomes a device by which to admit solar radiation, walls and floors become thermal storage devices, etc.

Dosi frames as technology as occupying a trajectory within a "technological paradigm." Used to characterize passive solar design, the Dosi model suggest that this technology springs from a new technological paradigm. Dosi defines the paradigm as an "outlook" and "definition of the relevant problems." What have the "difficult puzzles" traditionally been in residential design and construction? A simple enumeration will not suffice here. The "puzzles" vary by participant and process stage. To distinguish the participants, their roles, and their respective definition of the relevant problems, I borrow from President's Commission on Urban Housing in Nelkin, 1971. A network of participants is displayed in Figure 37.

Residential buildings are traditionally programmed by a relatively fixed set of objectives dictated by the housing market: optimizing the trade-off between gross floor area and the provision of site amenities like landscaping and privacy, and minimizing initial cost. Energy efficiency is a concern, but it is third-order at best: *Barron's Real Estate Handbook* mentions energy efficiency as the 20th item that sellers should take into account in making their homes as marketable as possible. Philip Ng, Chief Executive Officer of *Far East Organization* and son of Ng Teng Fong, Singapore's preeminent residential housing developer, notes that the three most important determinants of real estate prices are location, location, and location. It is no wonder that energy efficiency is left by the wayside. Because passive solar technology requires recognizing all a building's components as well as their relationship to the site and even the rest of the community as determinants of energy efficiency, it represents a new "outlook" and "definition of the 'relevant' problems," according to Dosi's model. The new relevant problem with passive

	(1) PREPARATION → PHASE	(2) PRODUCTION → PHASE	(3) DISTRIBUTION ⇆ PHASE	(4) SERVICE PHASE
Participants	Developer Land owner Lawyers Real estate brokers Title companies Architects and engineers Surveyor Planners and consultants ↓	Developer Landing institutions (interim and permanent) FHA, VA, or private mortgage insurance company Contractors Subcontractors Craftsmen and their unions Material manufacturers and distributors Building code officials Insurance companies Architects and engineers ↓	Developer Real estate brokers Lawyers Lending institutions Title companies FHA, VA, or private mortgage insurance company ↓	Owner Maintenance firms and employees Property management firms Insurance companies Utility companies Tax assessors Repairmen, craftsmen and their unions Lending institutions Architects and engineers Contractors Subcontractors Material manufacturers and distributors Local zoning officials Local building officials ↓
	a. Land acquisitions b. Planning c. Zoning amendments	a. Site preparation b. Construction c. Financing	a. Sale (and subsequent resale or refinancing)	a. Maintenance and management b. Repairs c. Improvements and additions
Influences	↑ Real estate law Recording regulations and fees Banking laws Zoning Subdivision regulations Private deed restrictions Public master plans	↑ Banking laws Building and mechanical codes Subdivision regulations Utility regulations Union rules Rules of trade and professional association Insurance laws Laws controlling transportation of materials	↑ Recording regulations and fees Real estate law Transfer taxes Banking laws Rules of professional association	↑ Property taxes Income taxes Housing and health codes Insurance laws Utility regulations Banking laws Union rules Rules of trade and professional association Zoning Building and mechanical codes Laws controlling transportation of materials

Figure 37 Participants in the building process, their roles and influence (source: President's Commission on Urban Housing, 1967, in Nelkin, 1971).

solar design is quite simple: configuring the building in a way that enables solar heat gain, lighting, or ventilation according to the means described in Chapter 5. The altered paradigm arises not from building configuration itself nor from the simple idea of energy efficiency. It arises specifically from the use of building configuration to enable energy efficiency.

Although this new mode of thinking may map reasonably well onto some actors' interests (in particular, the interest of the householder in minimizing energy expenditure), this interest does not coincide well with the relevant actor's role or abilities[5]. Indeed, passive solar design can be interpreted as a new technological paradigm.

What are the implications of these characterizations? Henderson and Clark draw a strong link between the nature of an architectural innovation and the ability of existing firms to adapt to its production. Recall,

> architectural innovations destroy the usefulness of the architectural knowledge of established firms, and that since architectural knowledge tends to become embedded in the structure and information-processing procedures of established organizations, this destruction is difficult for firms to recognize and hard to correct.

The authors attribute destruction and difficulty to three specific devices: communication channels; information filters; and problem-solving strategies. "An organization's communication channels, both those that are implicit in its formal organization (A reports to B) and those that are informal ('I always call Fred because he knows about X') develop

[5]One piece of supporting data here is the frequent association of passive solar design with custom-built homes. Here the energy expenditure-minimizing interest of the homeowner is coincident with an ability to demand it. Some might object that all householder interests should be efficiently translated into what gets built through the market mechanism. While I could be convinced that the market values energy efficiency within the existing technological paradigm, no such valuation occurs with respect to independent efficiency measures. Barnett, in the Rocky Mountain Institute's *Primer on Sustainable Building* offers the following corroboration: "In the intensely competitive housing market, the safest path is the tried-and-true. In typical 'Catch 22' fashion, some use the excuse that the 'marketplace' is not interested in green buildings and we know that because no one is building them. However, if no one is offering such buildings, how can the marketplace respond? Those builders who take the risk are well rewarded, but if no one in a given area has tried it, few have the leverage or boldness to be the first. The bottom line is that building green is a new challenge for industry that often feels challenged enough as it is."

around those interactions within the organization that are critical to its task" (Galbraith, 1973; Arrow, 1974 in Henderson and Clark, 1990). As such, these communication channels "will come to embody its architectural knowledge of the linkages between components that are critical to effective design" (Henderson and Clark, 1990). "The information filters of an organization also embody its architectural knowledge. An organization is constantly barraged with information. As the task that it faces is stabilizes and becomes less ambiguous, the organization develops filters that allow it to identify immediately what is most crucial in its information stream" (Arrow, 1974; Daft and Weick, 1984 in Henderson and Clark, 1990). "Over time, engineers acquire a store of knowledge about solutions to the specific kinds of problems that have arisen in previous projects. When confronted with such a problem, the engineer does not reexamine all possible alternatives but, rather, focuses first on those that he or she has found to be helpful in solving previous problems." In this way, "problem-solving strategies also reflect architectural knowledge, since they are likely to express part of an organization's knowledge about the component linkages that are crucial to the solution of routine problems" (Henderson and Clark, 1990). Can the same effect not be said to apply to the range of participants in the building process? Each set of actors has a unique conception of the critical success factors of their activity. Developers are used to maximizing the gross floor area buildable on a particular site, as well as the quality and cost of that space. Architects are used to implementing the size and programming interests of the developers. Engineers are used to specifying safe, functional, and energy-efficient systems in the architect's conception of the building. Buyers are used to evaluating purchase choices based on what is offered in the market at a particular time and their relative prices. The Henderson and Clark model predicts difficulty for a firm in adapting its methods of production to an architectural innovation on account of the communication , information-filtering and problem-solving tendencies of its employees. In the residential sector, these devices should be expected to each actor in the process individually. But more importantly, the effect of these devices is likely to be highly exaggerated by the allocation of different responsibilities in the design-development cycle to different actors. If intra-firm communication channels tend to lack adaptability to architectural innovations, what about the traditional relationship between developers and buyers, or architects and engineers? Henderson and Clark predict hindrances in the production of passive solar homes as a result of the architectural nature of the innovation. This effect is exaggerated by the organization of the industry which is even more likely than an individual firm to display the static tendencies that are responsible for these hindrances. Because passive solar technology should be expected to diffuse in an evolutionary manner, these constraints will hinder not only the development of this innovation, but its diffusion as well.

The implications of the Dosi characterization are independently similar. One immediate prediction is an "exclusion effect," whereby the efforts and imaginations of relevant individuals and organizations are "blind" to technological possibilities outside the paradigm. This is consistent with Henderson and Clark's channels, filters, and strategies analysis. This effect is partially corroborated by Sherwood's (1997) remark that passive solar houses tend to occur in "clumps." That is, an initial instance of technology adoption tends to spur other instances within the same community or locality.

Dosi's model also incorporates the idea that a mature industry reflects the existing technological paradigm. In this case, the building process as well as the nature of the relationships between participants reflects the existing paradigm. David Pellish (1990) of the U.S. Department of Energy offers the following description of the process of designing the exterior wall of an office building:

> First, the architect determines the wall's shape and general assembly of different materials. After that, the structural engineer proposes ways to support that wall assembly. The mechanical engineer may suggest appropriate insulation materials and the required thermal properties of the windows. Unlike the symphony orchestra, which must respond to the conductor's baton in absolute unison, the building design team more often acts like a relay running team, where the baton is handed over from one runner to another.

In the case of residential houses, the roles are similarly broken up. Passive solar design thus requires re-orientation within not one, but many of them, creating an obstruction to rapid diffusion.

In summary, because passive solar technology should be expected to diffuse in an evolutionary manner where to a large extent the innovation process must reoccur in every instance of adoption, an analysis by model of innovation is also relevant to understanding the forces that drive diffusion. This analysis has been the topic of this section. Both the Henderson and Clark and Dosi models come to similar conclusions: passive solar technology is "architectural," and represents a new "technological paradigm." This characteristic of a technology is associated, for a variety of reasons, with firm difficulty in adapting their activities to its production. In this case, this difficulty exists not only in production, but also in adoption. Furthermore, the devices that are likely to cause this difficulty are exacerbated by the structure of the building industry and building process, where activities are split not between separate company departments, but between totally different sets of firms and actors.

CONCLUSION

The effect of the characterization of passive solar technology by models of innovation has been to demonstrate that making buildings energy-efficient by rearranging the parts represents a new technological paradigm, with an associated new outlook and definition of the relevant problems. This combines with the earlier insight that with passive solar technology the innovative aspects of diffusion cannot be differentiated and results in an evil synergy where widespread adoption of the technology is slow and laboured. The mature housing industry and the traditional design-build process reflect the existing technological paradigm. The net effect is that the diffusion of passive solar technology is likely to be subject to a great deal of friction. This prediction is corroborated by the historical diffusion rates of the technology, which are surprisingly low.

REFERENCES

ABERNATHY, William J. and James M. Utterback, 1978. "Patterns of Industrial Innovation," *Technology Review*, Vol. 80, No. 7 (June/July).

BARNETT, Dianna Lopez and William D. Browning, 1995. *A Primer on Sustainable Building*. Rocky Mountain Institute, Snowmass, Colorado, 134 pp.

BROWN, Lesley, editor, 1993. *The New Shorter Oxford English Dictionary on Historical Principles*, Clarendon Press, Oxford.

CAINARCA, G. C., M. G. Colombo, and S. Mariotti, 1989. "An Evolutionary Pattern of Innovation Diffusion. The Case of Flexible Automation." *Research Policy* Vol. 18, pp. 59-86.

CALDART, Charles C. and Nicholas A. Ashford, 1997. *Law, Technology and Public Policy*. Class taught in the Technology and Policy Program at the Massachusetts Institute of Technology, Cambridge, MA.

DAVID, Paul A. (1986). "Technology Diffusion, Public Policy, and Industrial Competitiveness," in Ralph Landau and Nathan Rosenberg, Eds., *The Positive Sum Strategy: Harnessing Technology for Economic Growth*. National Academy Press, Washington, D.C.

DOSI, Giovanni, 1982. "Technological Paradigms and Technological Trajectories," *Research Policy*, Vol. 11, pp. 147-162.

EIA (Energy Information Administration), *Annual Review of Energy 1995*.

FOSTER, Richard N., 1988. "Timing Technological Transitions," in Tushman and Moore, Eds., *Readings in the Management of Innovation* (Second Edition), Ballinger, Boston, MA, pp. 215-228.

HARRIS, Jack C. and Jack P. Friedman, 1993. *Barron's Real Estate Handbook* (3rd Edition), Barron's Educational Services, New York.

HENDERSON, Rebecca M. and Kim B. Clark, 1990. "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," *Administrative Science Quarterly*, Vol. 35, pp. 9-30.

HERSEY, Karen, 1991. "Copyrights, Patents, and Trade Secrets -- A Brief Primer," *Information System News*, Massachusetts Institute of Technology, Cambridge, MA.

HOUGHTON, David et. al., 1996. *E Source Technology Atlas Series Volume 3: Space Heating*, E Source, Inc., Boulder, CO.

MARQUIS, Donald G., 1988. "The Anatomy of Successful Innovations," in Tushman and Moore, Eds., *Readings in the Management of Innovation* (Second Edition), Ballinger, Boston, MA, pp. 79-87.

MARTIN, Thomas E. (Principal, Martin Associates Architects, Toronto, Ontario), July, 1997. Personal Communication.

MOREHOUSE, Jeffrey H., 1997. "Passive Solar Heating, Cooling and Daylighting," in Kreith, Frank and Ronald E. West, editors. *CRC Handbook of Energy Efficiency*, CRC Press, New York, pp. 849-902.

NELKIN, Dorothy, 1971. *The Politics of Housing Innovation: The Fate of the Civilian Industrial Technology Program*. Cornell University Press, Ithaca, NY, 124 pp.

NG, Philip (Chief Executive Officer, Far East Organization, Singapore), July, 1997. Personal Communication.

PELLISH, David M., 1990. "Buildings in the Next Century," in Jefferson W. Tester, David O. Wood, and Nancy A. Ferrari, editors. *Energy and the Environment in the 21st Century*, MIT Press, Cambridge, MA.

SHERWOOD, Larry (Executive Director, American Solar Energy Society, Boulder, CO), July, 1997. Personal Communication.

TEECE, David J., 1988. "Profiting from Technological Innovation: Implications for Integration, Collaboration, Licensing and Public Policy," in Tushman and Moore, editors, *Readings in the*

Management of Innovation (Second Edition), Ballinger Publishing Company, Boston, MA, pp. 621-647.

7

The Effect of Regulation

INTRODUCTION

The effects of regulation must be considered in an assessment of the dynamics of technological change and technology adoption in residential buildings. However, as in the case of efficiency technology assessment by model of innovation and diffusion, this is a gargantuan task. The strategy will be to focus on a small subset of relevant regulation. This allows us to draw meaningful conclusions about a representative piece of regulation from which some general attributes of regulation in the sector can be inferred.

Control of building and land use is exercised through direct municipal regulation, indirect public control, private control, and federal regulation (Kelly, 1959, pp. 303). Direct municipal regulation of land and land development is embodied in building codes and zoning ordinances. Indirect public controls include "the imposition of taxes, the location of major roads and extension of municipal services, the power to take land by eminent domain, and the power to add land to a municipal corporation by annexation" (Kelly, 1959, pp. 303). Private controls include deed restrictions and the lending regulations of financial institutions. Federal regulation takes the form of rules and actions carried out by federal agencies such as the Department of Housing and Urban Development, the Department of Energy and the Environmental Protection Agency.

It is clear from the multiplicity of regulations and controls that building and land use control is decentralized and as a result accountable to a large number of objectives that are not necessarily consistent with the efficient use of energy. More efficient use of energy can encouraged at each of these points of control, and each would make a valid discussion and analysis. We briefly discuss a form of local level regulation, building codes, and then analyse the treatment of technology under a federal regulation of household appliance efficiency.

7.1 Overview of Federal Regulation of Energy Use in Buildings

There is no uniform legislation dealing with energy use in buildings. The current and past control of energy use in buildings has been exercised through an array of Congressional mandates to a different agencies, mostly the Department of Energy. Relevant federal legislation is listed in Table 9. This chronology of regulation acts on energy use in the building sector through a variety of different mechanisms, including:

- appliance labeling and standards (EPCA 1975);
- the establishment of state energy conservation programs (EPCA 1975);
- the development of conservation programs and standards for federal buildings (EPCA 1975);
- the establishment of energy conservation standards for new buildings (ECPA 1976);
- weatherization assistance for low-income persons (ECPA 1976);
- authorization to provide demonstration grants and loan guarantees to stimulate conservation measures in existing buildings (ECPA 1976);
- authorization for states to establish energy extension services (NEESA, 1977);
- authorization of federal residential conservation tax credits (NETA, 1978);
- the authorization of the Residential Conservation Service (RCS);
- the establishment of the Commercial and Apartment Service (ESA 1980) (Sources: Hirst et. al., 1986; the United States Code).

Table 9 Federal Regulation of Building Energy Efficiency

Energy Policy and Conservation Act (Pub. L. 94-163; 42 U.S.C. Sec. 6201-6422) including: • *National Appliance Energy Conservation Amendments of 1988* • *National Appliance Energy Conservation Act of 1987* • *Energy Policy and Conservation Amendments Act of 1985*	1975
Energy Conservation and Production Act (Pub. L. 94-385; 42 U.S.C. Sec. 6801-6892) including: • subchapter II, *Energy Conservation Standards for New Buildings* • subchapter III, *Energy Conservation in Existing Buildings Act of 1976*	1976
National Energy Extension Service Act (Pub. L. 95-39)	1977
National Energy Tax Act (Pub. L. 95-618)	1978
National Energy Conservation Policy Act (Pub. L. 95-619; 42 U.S.C. Sec. 8201-8287c) including: • *Federal Energy Management Improvement Act of 1988* • *Conservation Service Reform Act of 1986* • *Energy Policy Act of 1992* (Pub. L. 102-486)	1978
Energy Security Act (Pub. L. 96-294)	1980

(Sources: Hirst et. al., 1986; 42 U.S.C.)

Each of these regulatory actions has in some way affected the energy-intensity of buildings, but these effects are large in number, complex, and difficult to discern from the effects of the multiplicity of forces acting on energy use in the buildings such as occupant income, fuel prices, structural changes, lifestyle changes , and climate variation.

For our purposes it is not necessary to distinguish the precise action of these disconnected regulations. Based on the work of Myers (1987), we know that technological change has incrementally driven efficiency improvements in residential buildings. Based on a vision of how regulation can harness the power of technology, we can make a critical evaluation of current regulation, and eventually recommend a strategy for the future. I briefly discuss building codes and then examine of a major piece of regulation, the *National Appliance Conservation Act of 1987* (an amendment of the *Energy Policy and Conservation Act*). This statutory mandate has current relevance and directly affects the use of technology in the building sector.

7.2 BUILDING CODES

The form and configuration of buildings is partially controlled through building codes. Codes establish "minimum construction criteria to protect life and property" (Goldberg, 1991). In most states building codes also regulate building energy efficiency. Although building codes do not exercise a dominant effect on the diffusion of passive solar systems, they nonetheless have important implications for the implementation of new technology in the sector generally. Consequently it is important for a discussion of technology-based residential energy efficiency to be informed of the nature of building codes and the process by which they are adopted and implemented.

A. The Nature of Building Codes and Building Energy Codes

There are two types of codes, prescriptive and performance-based. "A *prescriptive* standard uses simple listings of requirements for determining whether a building 'passes' or 'fails.'" Building energy *performance* standards establish an efficiency target, or set of targets" (Houghton et. al., 1996). Usually this target is specified in thermal requirements per unit of floor area, per unit of building conditioned volume, or one of these indices normalized to a climate factor such as "heating degree days." Codes usually incorporate prescriptive and performance-based options.

Most states stipulate that municipalities adopt one of three model building codes, that issued by the Building Officials and Code Administrators (BOCA), the International Conference of Building Officials (ICBO), or the Southern building Code Congress International (SBCCI). The model codes are adopted on roughly a regional basis *(Figure 38)*, and modified to suit local needs. The codes are also modified "in deference to pressure from trade groups," as discussed in Houghton et. al., 1996. The model codes themselves are developed by consensus between manufacturers and officials, and incorporate only practices and materials that are "within existing boundaries of knowledge" (Slaughter, 1994). Consequently, building codes are not technology-forcing by any stretch of the imagination. Rather, codes reflect the current "standard practice" in design and construction.

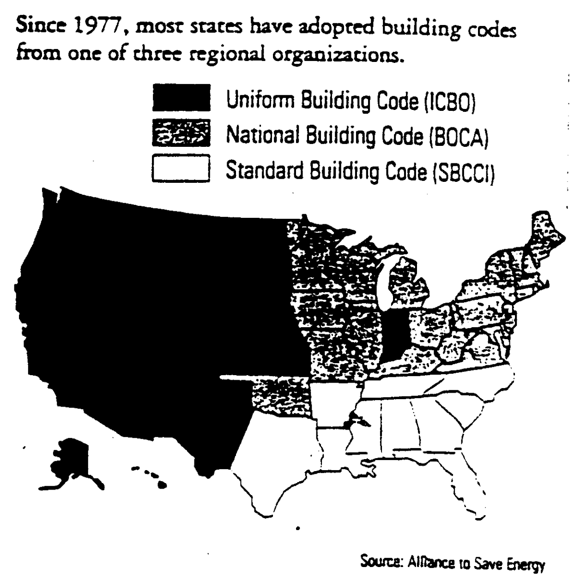

Figure 38 U.S. building code regions (source: Alliance to Save Energy in Houghton et. al., 1996).

Furthermore, although performance standards should theoretically be preferred over prescriptive standards because they do not constrain the manner in which efficiency requirements are met (allowing for innovation and cost-saving) the opposite is in fact often true. As Houghton et. al, 1996 discuss, builders actually often prefer codes that allow them the ease of "following a recipe."

In the specific dimension of residential energy-efficiency, there are three common model codes:

- CABO Model Energy Code (MEC) (most recent update 1995; 1983, 1986, 1989, 1992, 1993 versions also in use);
- American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) standard 90.2;
- BOCA National Energy Code (most recent update 1993; 1981, 1984, 1987, and 1990 versions also in use) (source: Smith and Nadel, 1995).

B. The Process of Energy Code Adoption

Energy codes are adopted in one of three ways: by states, through legislation; by states, through regulation; or by local jurisdictions, through ordinance (Conover et. al., 1992 in Smith and Nadel, 1995). A recent piece of federal legislation, The Energy Policy Act of 1992 (EPAct) "requires states to certify within two years that they have reviewed and updated their residential building code to meet or exceed the requirement of the Council of American Building Officials' (CABO) Model Energy Code of 1989, a consensus code developed with broad industry participation, and it sets up a procedure for the Secretary to update this requirement if CABO updates its code" (Congressional Record, 1992). The most recent provision is for states to meet or exceed CABO Model energy Code 1992. However, implementation of this regulation is weak: as of June, 1994, 26 states did not meet or exceed 1992 MEC; 2 states marginally did not meet it; 17 states met or exceeded

1992 MEC; and 2 states marginally met or exceeded it (Klevgard et. al., 1994 in Smith and Nadel, 1995).

C. Energy Code Implementation

As local-level regulations, codes are enforced at the city or town level, by local building inspectors. Compliance is problematic. Smith and Nadel, 1995, who comprehensively reviewed the major work on energy code compliance, note:

> energy codes have been traditionally considered less important as compared to health, safety, and fire codes. The range of knowledge needed by officials to enforce fire, health and safety, mechanical, electrical, and/or energy codes adequately is, obviously, vast. Since most enforcement agencies have limited budgets for salaries and training, departments are usually filled by people with backgrounds in the construction trades who get little additional job training. Given their backgrounds and the relative importance of life-safety issues as compared with energy, enforcement emphasis is naturally placed much more on health, safety, and fire code compliance. In some cases, code officials are not even familiar with the energy code.

D. Conclusion

Despite these limitations, energy codes are useful in promoting efficiency. Houghton et. al., 1996 highlight the positive effects of energy code in helping to: (1) drive inferior practices out of the market; (2) reinforce professional education; (3) "make a market" for energy-efficient buildings; (4) accelerate the introduction of new technologies. Whether or not one buys the specifics of this cheerful view of the role of energy codes, code efficiency is associated with improved conventional practice *(Figure 39)*.

The energy efficiency of homes built according to the Model Energy Code (MEC) has led, by a substantial margin, advances in the efficiency of conventional building practice.

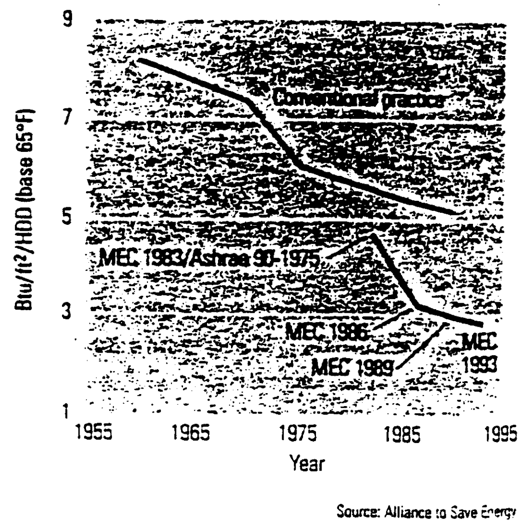

Figure 39 The association of changes in the CABO Model Energy Code with improved conventional building practice.

Nevertheless, it is not clear that the nature of the code itself is an independent, positive effect on efficiency. At minimum, the codes raise awareness and mitigates profligate energy use in new additions to the housing stock.

7.3 The Regulation of Energy Use in Household Appliances

A. *Background*

In 1993, the latest year for which data is available, U.S. households consumed 103.6 million Btu in energy. Refrigerators consumed 4.7 million Btu and appliances used 20.1 million Btu (EIA, 1993). From the work of Schipper and Meyers (1992), we have a rough understanding of the evolution of residential appliance energy use. The trend in aggregate consumption has been a steady climb 1982-1993 (as described in Chapter 3). Schipper and Meyers distinguish structural (based on appliance ownership levels) and intensity (based on unit energy consumption) effects. Trends in these respective areas are shown in the following tables.

Table 10 Appliance ownership in OECD countries (units per 100 households) (source: Schipper and Meyers, 1992).

	Year	Refrigerator	Freezer	Clothes washer	Dishwasher
United States	1973	99	34	70	25
	1988	113	35	73	43
Japan	1973	100	< 1	98	< 1
	1988	117	3–5	99	3–5
Europe-4	1973	83	13	69	5
	1988	114	45	89	21
Scandinavia-3	1973	93	50	56	7
	1987	106	72	77	27

Table 11 Appliance unit energy consumption (kWh/year) (source: Schipper and Meyers, 1992).

	1973	1980–81	1986–87
Refrigerator[a]			
United States	1450	1380	1310
Japan	395	645	610
West Germany	770	670	600
Clothes dryer			
United States	1050	1050	990
Japan	~ 355	355	355
West Germany	475	425	270
Dishwasher			
United States	365	250	250
West Germany	800	625	310

The authors estimate that appliance electricity use per capita increased by 23 percent between 1972 and 1987. Over the same period, the impact of structural change was + 37 percent while the impact of change in intensity was - 13 percent.

Based on an analysis of appliance efficiency and use trends in OECD countries, Schipper and Hawk (1991) draw the following conclusions:

- Most household electricity using technologies are significantly more efficient today than in 1973, principally because new, more efficient equipment has replaced older equipment.

- Although these improvements in appliance efficiency have put downward pressure on unit consumption, unit consumption for most appliances has not declined proportionately. Changes in the frequency/level with which appliances are used, and in appliance features, options and size have generally acted to increase electricity unit consumption.

- New appliances and other electricity using systems are more efficient than older ones that characterize the stock, but the rate of improvement of new appliances has slowed or halted and consumer indifference to saving electricity is rising.

- A great technical and economic potential exists for increasing electricity use efficiency in future appliances, but policies may be required to provoke the exploitation of that potential by both manufacturers and by consumers. The efficiency improvement in most end-use technologies between 1973 and 1985 was driven mainly by higher electricity prices and a few informal agreements between authorities and the appliance industry, as well as standard in California. Technological changes that resulted in cost reduction (e.g. replacement of fibreglass insulation with polyurethane foam in refrigerators and freezers) and automation of production lines were important enabling factors. The slowdown in the improvement of electricity efficiency is due to weakening public and private interest in saving energy or electricity which, in turn, is primarily a result of lower real electricity prices. Thus accelerating the pace of efficiency improvements requires policies and higher electricity prices.

B. The National Appliance Energy Conservation Act of 1987

The *National Appliance Energy Conservation Act of 1987* (42 U.S.C. Sec. 6291-6309), or NAECA, develops an energy conservation program for (non-automobile) consumer products. It dictates a maximum allowable energy use per year for refrigerators, refrigerator-freezers, freezers, room air conditioners, central air conditioners and heat pumps, water heaters, pool heaters, direct heating equipment, furnaces, dishwashers, clothes washers, clothes dryers, fluorescent lamp ballasts, kitchen ranges and ovens, and other products (Sec. 6295 (b) - 6295 (i).) These standards are required to be re-published on a regular basis. The most recent standards govern refrigerator energy use and were promulgated on 28 April, 1997.

Important criteria for prescribing new or amended standards are that no standard may be less energy-efficient than an earlier one and that any standard "be designed to achieve the maximum improvement in energy efficiency which the Secretary determines is technologically feasible and economically justified" (Sec. 6295 (l) (2) (A)). In determining whether a standard is economically justified, the Secretary is to consider the economic impact of the standard on manufacturers and consumers, the savings in operating costs throughout product life, the total projected energy savings likely to result from the standard, the impact of any lessening of competition, the need for national energy conservation, and any other relevant factors.

The standards are updated through a negotiation process. In developing the most recent rule, for example, the DOE "relied substantially on a joint recommendation negotiated by refrigerator manufacturers and their trade association, energy efficiency advocates, electric utilities, and state energy offices" (DOE, 1997). The resulting standards are strongly biased in favour of the *status quo*. For example, the possible achievements of the horizontal-axis clothes washer and the heat pump water heater, two energy-efficient appliance technologies considered to be cost-effective and timely by such organizations as the American Council for an Energy-efficient Economy (ACE^3), were blocked in the latest round of standard-setting by manufacturers (Suozzo, 1997). Suozzo, a buildings expert with ACE^3, reckons that technological transformation almost never occurs through updated standards. Rather, it occurs through "market transformation initiatives," technology changes that occur slowly in the right environment, consisting of manufacturer willingness, market conditions, government incentives and policy, etc.

Does the process of negotiated rulemaking preclude the ability to force technology through regulation? Does the use of industry data and models to determine issues of technological feasibility and economic justification introduce unacceptable bias? Have the critical issues of (1) Economies of scale from scaled-up production, (2) "learning curve" effects on the costs of compliance for regulated firms, (3) unanticipated benefits of technological change (Ashford, 1994) been taken into account in the design of appliance regulations?

These questions touch on significant and real problems with the current regulatory approach. Clearly manufacturers are not rushing to develop new technologies. In order to decide precisely to what extent the new refrigerator standards, for example, are a manifestation of the *status quo* one might become a refrigerator expert and make a comprehensive technology assessment. But it is enough to look at the process. Allowing an industry with its own agenda to negotiate the energy efficiency standards to which it will be subject points to a lack of vision and a failure to take explicit account of the possibilities that improved technology can offer. This regulatory paradigm rewards those who cling to the existing technological *status quo* rather than those who pursue opportunity.

The DOE employed a computer model to assess the "likely impacts of standards on manufacturers and to determine the effects of the standards on the industry at large." "The module which estimates the impact of standards on total industry net present value is version 1.2 of the Government Regulatory Impact Model (GRIM), dated March 1, 1993, which was developed by the Arthur D. Little Consulting Company (ADL) under contract to AHAM [the Association of Home Appliance Manufacturers], the Gas Appliance Manufacturers Association (GAMA), and the Air-conditioning and Refrigeration Institute (ARI)." Is this further reliance on industry for technology assessment data questionable? At minimum, it is not technologically pro-active.

Of course appliance efficiency is only one aspect of residential efficiency generally, and indeed it is the easiest to analyze from a technology viewpoint. Other contributors to consumption like space heating are more difficult to get a handle on because the efficiency innovations are not as a rule embodied in physical products, but more in construction practices and proper installation of materials (such as joint sealing and building vapor and air barriers). Consequently they cannot be modeled with the standard product diffusion S-curve.

Similarly, NAECA is only one of a multiplicity of regulations acting on the building sector. As discussed in Section 7.2, the *Energy Policy Act of 1992* (EPAct) "requires states to certify within two years that they have reviewed and updated their residential building code to meet or exceed the requirement of the Council of American Building Officials' (CABO) Model Energy Code of 1989, a consensus code developed with broad industry participation, and it sets up a procedure for the Secretary to update this requirement if CABO updates its code" (Congressional Record, 1992). EPAct also adds standards for some fluorescent and incandescent reflector lamps, plumbing products, electric motors, and commercial water heaters and Heating, Ventilation, and Air Conditioning (HVAC) systems (NEIC, 1997).

An analysis of NAECA does not provide a comprehensive look at the treatment of technology under federal-level building sector regulations, but it does provide a representative look. Building codes, including the Model Energy Code that must be considered by states under EPAct are developed by consensus between manufacturers officials, and incorporating only practices and materials that are "within existing boundaries of knowledge" (Slaughter, 1997). New technologies are accepted only gradually in building codes (Martin, 1997).

Current regulation considers technology, but in a lame manner. Standards are decided in extended negotiations between manufacturers who dread cost increases and regulators who nevertheless rely on them for data with which to arrive at decisions. No strategy exists to take advantage of what technology can be made to do: simultaneously improve building systems along the dimensions of cost and energy-efficiency. In Chapter 8, I explore how a diffusion-driven technology strategy might be designed.

CONCLUSION

The most evident feature of public control over residential energy efficiency is its discombobulated nature. Control is exercised at different levels, under different sets of objectives, and subject to varying qualities of enforcement. This is partially a result of the nature of building systems themselves. They are complex, and incorporate elements from a variety of different productive activities that cannot be sensibly regulated together: appliance manufacturers and residential housing contractors, for example. This lack of organization is also, however, partially the result of a lack of vision on how to realise the amazing energy efficiency gains available in the sector, abundantly documented in a regulatory analysis of NAECA. Some believe, as does Paul David (1986), that this is characteristic of the management of technology generally in the United States, and in particular, that "the United States does not have a well-articulated set of policy goals with regard to the development and utilization of its technological capabilities, much less a coherent, integrated program directed to the attainment of such goals." Combined with the lack of propensity of many innovations to diffuse quickly on their own, this state of regulation is an unfortunate circumstance. In the next chapter I explore what can be inferred from this regulatory analysis and the previous analysis of passive solar technology.

REFERENCES

ASHFORD, Nicholas A., 1994. "An Innovation-Based Strategy for the Environment." In: Finkel, A.M. and D. Golding, Eds. *Worst Things First? The Debate Over Risk-based National Environmental Priorities.* Resources for the Future, Washington, DC.

ASHFORD, Nicholas A. and Charles C. Caldart, 1997. *Law, Technology and Public Policy.* Class taught in the Technology and Policy Program at the Massachusetts Institute of Technology, Cambridge, MA.

CONGRESSIONAL RECORD (Vol. 138), 1992. House Report 102-474 (I), pp. 1993.

CONOVER, David R., Ron E. Jarnagin and Diana Shankle, 1992. "Commercial Building Energy Standards Implementation: Myth vs. Reality," in *Proceedings of the ACEEE 1992 Summer Study on Energy Efficiency in Buildings*, 6:27-6:34, American Council for an Energy-efficiency Economy, Washington, DC, referenced in Smith and Nadel, 1995.

DAVID, Paul A. (1986). "Technology Diffusion, Public Policy, and Industrial Competitiveness," in Ralph Landau and Nathan Rosenberg, Eds., *The Positive Sum Strategy: Harnessing Technology for Economic Growth.* National Academy Press, Washington, D.C.

DOE (Department of Energy), Office of Energy Efficiency and Renewable Energy, 1997. *Energy Conservation Program for Consumer Products: Energy Conservation Standards for Refrigerators, Refrigerator-Freezers and Freezers; Final Rule.* Federal Register, April 28, 1997 (Vol. 62, No. 81), pp. 23101-23116.

EIA (Energy Information Administration), 1993. *Household Energy Consumption and Expenditures 1993.* U.S. Department of Energy, Washington, D.C., 315 pp.

EIA (Energy Information Administration), 1994. *State Energy Data Report 1994.* U.S. Department of Energy, Washington, D.C.

EIA (Energy Information Administration), 1995. *Annual Energy Review 1995.* U.S. Department of Energy, Washington, D.C.

GELLER, Howard and Steven Nadel, 1994. "Market Transformation Strategies to Promote End-use Efficiency." *Annual Review of Energy and the Environment*, Vol. 19.

GOLDBERG, Alfred, 1991. *Design Guide to the 1991 Uniform Building Code* (3rd Edition), GRDA Publications, Mill Valley, CA.

HIRST, Eric, Jeanne Clinton, Howard Geller, and Walter Croner, 1986. "Chapter 9: Government Conservation Programs." In: O'Hara, F.M. Jr., Ed. *Energy Efficiency in Buildings: Progress and Promise*. American Council for an Energy-Efficient Economy, Washington, DC, 328 pp.

HOUGHTON, David et. al., 1996. *E Source Technology Atlas Series Volume 3: Space Heating*, E Source, Inc., Boulder, CO.

KELLY, Burnham, 1959. *Design and the Production of Houses*. McGraw-Hill, New York, pp. 2.

KLEVGARD, L. A., Z. T. Taylor and R. G. Lucas, 1994. *Comparison of Current State Residential Energy Codes with the 1992 Model Energy Code*, Pacific Northwest Laboratory, Richland, Washington, referenced in Smith and Nadel, 1995.

LEVINE, Mark D. and Paul P. Craig, 1985. "A Decade of United States Energy Policy." *Annual Review of Energy*, Vol. 10, pp. 557-587.

MARTIN, T.E. (Martin Associates Architects, Toronto, Ontario), 1997. Personal Communication.

MILLHONE, John P. and Kevin Y. Teichman, 1990. "Government Incentives for Improving Building Performance and Developing New Building Technologies." In: Tester, Jefferson W., David O. Wood, and Nancy A. Ferrari, Eds. *Energy and the Environment in the 21st Century*. MIT Press, Cambridge, MA, 1006 pp.

MYERS, Steven, 1987. "Energy Consumption and the Structure of the U.S. Residential Sector: Changes Between 1970 and 1985." *Annual Review of Energy*, Vol. 12, pp. 81-97.

NEIC (National Energy Information Center), 1997. "Residential Energy Efficiency and Appliance Standards" (Public information brief prepared by the staff of the Energy Efficiency and Renewable Energy Clearinghouse, Washington, DC, 13 pp.

NELKIN, Dorothy, 1971. *The Politics of Housing Innovation: The Fate of the Civilian Industrial Technology Program*. Cornell University Press, Ithaca, NY, 124 pp.

RUBIN, Edward S., Richard N. Cooper, Robert A. Frosch, Thomas H. Lee, Gregg Marland, Arthur H. Rosenfeld, Deborah D. Stine, 1992. "Realistic Mitigation Options for Global Warming." *Science*, Vol. 257, 10 July, 1992.

SCHIPPER, Lee and Stephen Meyers, with Richard B. Howarth and Ruth Steiner, 1992. *Energy Efficiency and Human Activity: Past Trends, Future Prospects*, Cambridge University Press, Cambridge.

SLAUGHTER, Sarah, 1997. *Innovation in Construction*. Class taught in the Department of Civil Engineering at the Massachusetts Institute of Technology, Cambridge, MA.

SMITH, Loretta A. and Steven Nadel, August, 1995. *Energy Code Compliance*, American Council for an Energy-efficient Economy, Washington, DC.

SUOZZO, Margaret (American Council for an Energy-efficient Economy, Washington, DC), 1997. Personal Communication.

U.S. BUREAU OF THE CENSUS, 1996. *Statistical Abstract of the United States: 1996* (116th Edition.) Washington, DC.

8

Improving Residential Energy Efficiency through the Application of Technology

8.1 Understanding Unrealized Energy Efficiency in Residential Buildings

At this time, we have developed a thorough understanding of two specific mechanisms: the special characteristics of passive solar technology that hinder its diffusion and the effect of federal regulation of household appliances on technology, which although incrementally beneficial to subsectoral efficiency, is altogether blind to the possibilities that technological change can offer.

In the context of developing a general characterization of the forces that drive efficiency in the sector, these initially seem like rather narrow insights. We understand the effect of regulation on appliance efficiency and the propensity of passive solar technology to diffuse slowly. What of the effect of regulation on the propagation of passive solar housing and the natural propensity of appliances of efficient appliances to be adopted? What of other end-use sectors? What of the explicit effect of the fragmented organization of the housing market, or the concentrated nature of the appliance industry? These are important effects and should be distinguished, perhaps in future research. Yet we can make powerful inferences as it is. An accurate picture of the technological dynamic of the residential sector has emerged, although some details remain out of focus.

First and foremost, building energy efficiency innovations are handicapped by their largely configurational nature. Figure 40 maps the potential energy savings in buildings by life cycle. Opportunities for efficiency are stacked in the early phases: programming, schematic design.

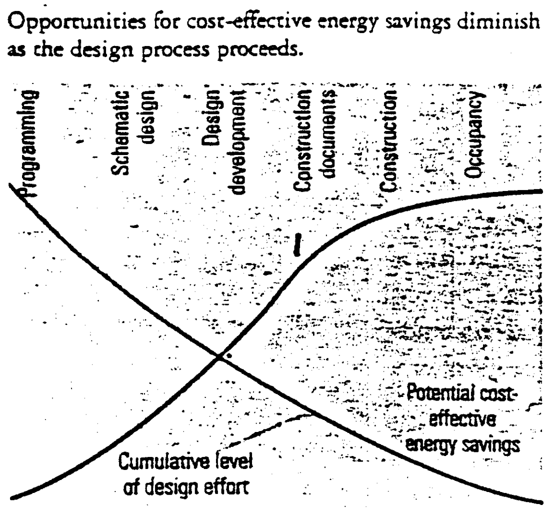

Figure 40 Energy savings opportunities by project life-cycle phase (source: Houghton et. al., 1996).

Building energy-efficient buildings is a task that requires optimizing the entire building system rather than simply one or more components. Although the principles of energy-efficient building are well-developed, they must be re-thought in every instance of adoption, by nature of the evolutionary action of the diffusion of these innovations. We can be fairly certain that this is the case with passive solar systems. We can also infer that this effect dominates the diffusion of energy-efficient building design generally: energy-conscious programming decisions; trading off HVAC system decisions with early-stage decisions; in fact, the majority of the early-stage opportunities shown in Figure 40.

It is also likely that this slowing effect is simultaneously reinforced by a number of other factors identified in the passive solar technology case study:

- The strong complementarities in efficiency technology diffusion, for example between favourable orientation and community layout;
- The structuring of the building process -- responsibility is split between a multiplicity of parties, reinforcing the dominant building paradigm and preventing any interest in energy efficiency from being manifested early in the design process;
- A general lack of appropriability of building energy efficiency innovations;
- The relatively small significance of energy expenditures at the individual project level (but obviously great significance at the aggregate level) -- it is unclear that even if given the opportunity through a modified structuring of the building process, this interest would be manifested through the market mechanism.

The overall effect is that the residential building sector is ill-disposed towards the easy diffusion of energy efficiency technology.

This unfortunate circumstance is only modestly helped by regulation, the second item of which we have some understanding. Under a consensual mandate and limited power to generate an objective understanding of the innovative potential of technology, the agency charged to manage appliance efficiency does so seemingly entirely on the regulated industry's terms. Regulation has discerned a middle ground but has neither envisioned, nor implemented a positive role for technology in the sector.

In all likelihood, this regulatory feebleness is not limited to appliance energy consumption. Although it is arguably not the proper role of building codes, they are similarly consensus-based and technologically conservative. Dorothy Nelkin, in *The Politics of Housing Innovation* (1971), arrived at corroborative conclusions in a case study of the *Civilian Industrial Technology Program*, a federal research and development and procurement program originally designed to revitalize the innovativeness of the housing sector.

It is clear that the energy efficiency innovation development and diffusion processes are frail in this sector. The reasons for this are straightforward: the configurational nature and lack of appropriability of the most effective efficiency technologies militate against their rapid diffusion. Regulation, where it might be expected to definitively redress this difficulty, is in contrast feckless and based on consensus with concentrated and hostile industry interests.

In Section 8.2, I look at how a strategy that harnesses the power of technology to overcome these problems and improve energy efficiency might be designed.

8.2 Framing a Technology-based Strategy

Every markets, regulated or unregulated, treats technology in some way -- once we understand how a particular environment is disposed towards the processes of innovation and diffusion, or its *innovative dynamic* (Ashford et. al., 1985), we can design a strategy taking a particular technology as the unit of analysis. This should be differentiated from an intervention that, for example, anticipates consumer response to price changes based on some microeconomic analysis. The dimensions of the problem are: (1) understanding the technological means by which efficiency might be improved -- innovation, diffusion, and the specific variables and effects within those processes; (2) understanding the channels through which these mechanisms operate -- individuals, institutions, industries, etc.; (3) developing specific, promising strategies. In Section A, I discuss technology-based means to improve efficiency. In Sections B and C, I briefly outline through what channels such a strategy could act and several strategy options to consider, respectively.

A. Technology-based Means to Improve Efficiency

In this thesis I have partially explicated the technology-environment dynamic in the residential building sector. We have implicitly discussed technology-based means to improve efficiency; two obvious choices are innovation and diffusion. Nicholas Ashford, a professor of technology and policy at the Massachusetts Institute of Technology, has developed a framework for assessing what type of technology-driven strategy to pursue. It is based on the characteristics of an industry and various parameters relating to the magnitude of the "transformation" desired. The conditions are listed in Table 12.

Table 12 Conditions favouring innovation-driven and diffusion-driven strategies.

Innovation	*Diffusion*
Large residual risks even after diffusion and/or high costs of diffusion	Distance from the efficient frontier
Innovative history or innovative potential	Noninnovative history; "essential" industry or product
Multimedia response desired	Single-medium response adequate
Multihazard industry	Single-hazard problem
Flexible management culture	Rigid management culture

(From: Ashford, 1994)

Ashford's framework is focused on risk reduction, which is slightly different from energy efficiency. The principles remain valid, however. Is the population of households far from the efficient frontier? Can efficiency be increased to *acceptable* levels using existing technology? The overabundance of existing technological options to reduce household energy consumption points to a diffusion-driven strategy. Yet it would be unwise to promote diffusion if it also meant prejudicing innovation[1]. For example, we may

[1]This requires simultaneously thinking about the means by which to stimulate diffusion and the interaction between innovation and diffusion mechanisms to avoid unintended consequences. This must be carried out on a technology-by-technology basis, for which we do not have the means in this thesis. I describe only directions suggested by the models of diffusion.

not want to stipulate a mandatory appliance efficiency standard based on the current maximum technologically feasible level. This will surely promote diffusion but may simultaneously eliminate a large incentive for innovation if any new technology developed by manufacturers is immediately required of them in production. We should strive to facilitate diffusion with no bias to industry's innovative capacity. This decided, we must think carefully about through which means, (identified through the application of the models) we should like to stimulate the system.

The easiest and most obvious type of technology to analyze from a diffusion model viewpoint are products that can be accurately characterized by the centralized model described in Mansfield, 1989 and Rose and Joskow, 1990. To increase efficiency, we would be interested in shifting the natural product, system, or practice penetration "S-curve" in the manner described in the following figure.

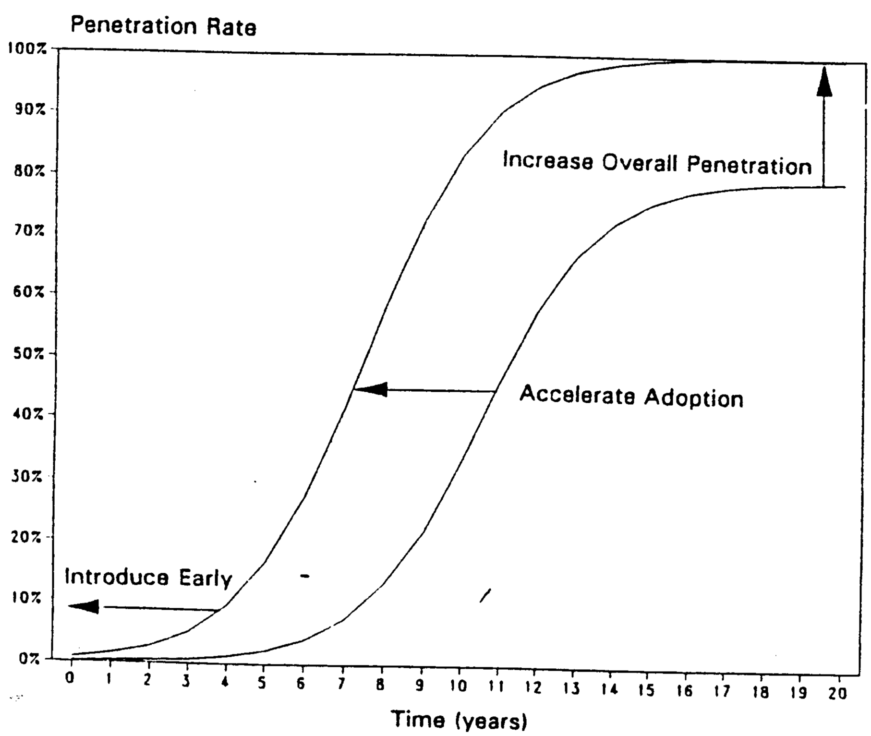

Figure 41 Approaches to increasing the penetration of energy-efficiency measures (from Nilsson, 1992 in Geller and Nadel, 1994).

This penetration curve diagram shows that, in the diffusion of an appropriate technology, we have the option to: move the time of first introduction forward; accelerate the frequency of subsequent technology adoptions; and increase the magnitude of overall penetration. To understand *how* we can achieve these effects, we turn to the specific forces driving diffusion.

Under this model, the factors that drive diffusion are the proportion of actual to potential users in a population of potential adopters, the average return from the innovation, and the time elapsed from first introduction of the technology in a particular industry in a particular country. Opportunity to adopt, operationalized by firm size, household disposable income, or some other variable, is also a factor when dealing with indivisible capital goods. Diffusion is positively related to these variables; consequently, we can promote diffusion by positively changing one or more of these variables. We would consequently want to: (1) take special measures to increase technology penetration in the early stages of diffusion or immediately following product introduction in anticipation of an accelerated subsequent diffusion rate; (2) increase the returns possible from a given innovation to both accelerate adoption and encourage deeper penetration; (3) take special measures to have energy efficiency innovations introduced earlier in a given industry, initiating the diffusion process earlier; (4) somehow provide a greater opportunity to adopt.

The limitations of this approach coincide with the limitations of the model in understanding technology diffusion in the residential buildings. Foremost is the model's basis in an ability to discern a clear and unchanging product. It is likely to work well in modeling devices such as horizontal-axis washing machines or compact fluorescent light bulbs. It is not likely to work well in modeling energy-efficient design practices such as the use of passive solar heating or favourable building orientation. Nor could it really be used to understand the diffusion of energy-efficient site or land-use planning. We could construct "penetration" curves for these design-based technologies (perhaps using percentage of additions to the stock that use some passive solar principles or percentage of communities that have implemented some sustainable design principles), but it does not follow that penetration or the proxy for penetration that we build will be driven by the factors of proportion of potential users, return from the technology, or time from first introduction. Many sustainable design principles are embodied in vernacular architecture developed centuries ago, but long since removed from common use. The time elapsed from first introduction variable thus seems improbable. Furthermore, we would have a hard time measuring the economic return from sustainable land-use planning. Even if we could, are the responsible decision-makers at all driven by market forces? Average return from the innovation would thus seem to be a similarly weak driver of diffusion.

For these more difficult cases we turn to alternative conceptions of technology diffusion. The evolutionary model proposed by Cainarca et. al. (1989) is based on the principle that the innovative aspects of diffusion cannot be differentiated and that technology changes and is modified locally as it diffuses. The forces driving diffusion were found to be the "inherent peculiarities" of the technology: the degree of appropriability; the potential for cross-fertilization between suppliers and users; technological complementarities; the expected profitability and cost of innovations.

Promoting "evolutionary" diffusion should thus be guided by these new variables. We would be interested in improving the appropriability of a particular innovation; enhancing the opportunity for cross-fertilization between suppliers and users; encouraging the diffusion of highly complementary technologies; and, naturally, increasing the profitability and reducing the costs of the relevant innovation(s)[2].

We might also look to Paul David's "technology access costs" for policy levers to accelerate the diffusion of energy efficiency technology: (1) the cost of obtaining and processing information on new technologies; (2) the cost of obtaining the materials or

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[2]In applying this model, it is reasonable to suggest that two conditions are required. First, the user should be technically competent in the manipulation of the innovation in order for it to able to evolve in their hands. Second, the users should be somewhat different in experience and circumstances. If the population of potential users was highly uniform, once a solution was developed, it would require little modification during the diffusion process, suggesting more "classical" mode.

equipment in which a new technologies is physically embodied; (3) the cost of specialized facilities, products, or services that are required in order to be able to exploit the innovation (David, 1986). We might promote diffusion by reducing or eliminating these costs.

B. Channels through which to Effect Efficiency

Once we understand through which specific actions we might accelerate the diffusion of energy efficiency innovations, it is important to arrive at a finer understanding of the channels and actors through which this acceleration might occur. In the residential building sector, the two basic channels are retrofit and new construction. To encourage retrofit activity, the relevant units to target would logically be homeowners themselves or agents that might act on their behalf, for example Energy Service Companies or electric utilities. To encourage efficiency in new construction, it would also be relevant to target homeowners and potential homeowners. However, in this case our interest would extend to a number of other participants in the design and development processes, including developers, contractors, architects, engineers, and suppliers. A thorough model of the relevant channels through which to enact a technology-based strategy is left to future research.

C. Promising Strategies

Developing and evaluating a range of technology-based strategy options is a thesis in itself and not our task here. The purpose of this section is identify directions that may prove useful with further investigation. I see the key challenge as encouraging diffusion, which ultimately imparts value to new energy efficiency technology, without prejudicing the development of new efficiency technologies. For example, setting an efficiency standard to a currently attainable, but very costly level will indeed promote efficiency but may also prevent industry from developing any such technologies in the future.

A dual approach may allow us to surmount this barrier. If, for example, companies are rewarded with a large government purchase order after attaining a challenging standard, this may serve to mitigate some industrial ill will. Involving large appliance buyers, for example -- public housing agencies, large developers, etc. -- may allow the procurement offer to be expanded and hence the attractiveness of the deal to manufacturers improved.

It may be impossible to somehow create greater appropriability around many of these configurational energy efficiency technologies. Instead, it is possible that devices as simple as information and demonstration programs may compel the relevant parties to think outside the traditional technological paradigm that governs residential design and construction. For example, Bujis and Silvester (1996) illustrate that sustainable housing programs in The Netherlands have served important technology-related functions in the organization of production, product development, and market development. Exploration of this and other ideas are left to future research.

CONCLUSION

This chapter first built a general characterization of the forces that move technology-related efficiency in residential buildings. This was done in an inductive manner, by generating conclusions based on the results of the technology and regulation case studies. It was argued that the inherent configurational nature of many energy efficiency technologies hinders their diffusion, and that regulation does little to remedy this effect.

The chapter also discussed how a technology-based strategy for realising improved energy efficiency might be framed, and identified specific means by which the diffusion of energy efficiency technology might be encouraged. Exploring the channels through which such a strategy would operate and the design of specific strategies were discussed briefly.

REFERENCES

ASHFORD, Nicholas A., 1994. "An Innovation-Based Strategy for the Environment." In: Finkel, A.M. and D. Golding, Eds. *Worst Things First? The Debate Over Risk-based National Environmental Priorities*. Resources for the Future, Washington, DC.

ASHFORD, Nicholas A., Christine Ayers, and Robert F. Stone, 1985. "Using Regulation to Change the Market for Innovation," *Harvard Environmental Law Review*, Vol. 9, No. 2, pp. 419-443; 462-466.

BARNETT, Dianna Lopez and William D. Browning, 1995. *A Primer on Sustainable Building*. Rocky Mountain Institute, Snowmass, Colorado, 134 pp.

BUJIS, Arjen and Sacha Silvester, 1996. "Demonstration projects and sustainable housing," Building Research and Information, Vol. 24, No. 4.

CAINARCA, G. C., M. G. Colombo, and S. Mariotti, 1989. "An Evolutionary Pattern of Innovation Diffusion. The Case of Flexible Automation." *Research Policy* Vol. 18, pp. 59-86.

DAVID, Paul A. (1986). "Technology Diffusion, Public Policy, and Industrial Competitiveness," in Ralph Landau and Nathan Rosenberg, Eds., *The Positive Sum Strategy: Harnessing Technology for Economic Growth*. National Academy Press, Washington, D.C.

GELLER, Howard and Steven Nadel, 1994. "Market Transformation Strategies to Promote End-use Efficiency," in Robert H. Socolow, Ed., *Annual Review of Energy and the Environment*, Vol. 19.

HOUGHTON, David et. a;., 1996. *E Source Technology Atlas Series Vol. 3: Space Heating*, E Source, Inc., Boulder, CO.

MANSFIELD, Edwin, 1989. "The Diffusion of Industrial Robots in Japan and the United States." *Research Policy*, Vol. 18, pp. 183-192.

NELKIN, Dorothy, 1971. *The Politics of Housing Innovation: The Fate of the Civilian Industrial Technology Program*. Cornell University Press, Ithaca, NY, 124 pp.

NILSSON, H., 1992. *Summer Study on Energy Efficiency in Buildings* Vol. 6, pp. 179-187. American Council for an Energy-efficient Economy, Washington, D.C., cited in Geller and Nadel, 1994.

ROSE, Nancy J. and P. L. Joskow, 1990. "The Diffusion of New Technologies: Evidence from the Electric Utility Industry." *RAND Journal of Economics*, Vol. 21, No. 3, pp. 354-373.

VENTRE, F. T., November, 1979. "Innovation in Residential Construction," *Technology Review*, pp. 51-59.

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Conclusion

This thesis has identified a number of characteristics of energy efficiency technology diffusion in the residential sector. The importance of such effects as the trade-off between initial and operating cost and capital indivisibility in long-term facilities was mentioned. For example, residential energy efficiency is improved largely through new additions to the housing stock, and the infrequently refurbished stock uses energy at a rate consistent with technology available at the time its constituent facilities were built. But the focus of this thesis was on a less familiar aspect of residential energy efficiency. Energy-saving technologies are largely configurational in nature and diffuse according to an evolutionary pattern, where the innovative aspects of diffusion cannot be sensibly differentiated. Some of these technologies, in particular passive solar systems, define a new technological paradigm. Furthermore, the benefits to these innovations often lack appropriability. The net result, demonstrated through the application of a number of management of technology models of the innovation and diffusion processes, is an occluded and slow diffusion process. In addition, where we might then have relied on regulation to make up the resulting unrealized efficiency, regulation has in fact been altogether weak.

The thesis also framed a technology-based approach for improving energy efficiency by stimulating technology diffusion. This is a prescriptive exercise where, based on a set of goals that technology is likely to be able to achieve, a strategy can be defined. The dimensions of the problem were identified as understanding the technological means by which efficiency might be improved -- innovation, diffusion, and the specific variables that drive these processes; understanding the channels through which these mechanisms operate -- individuals, institutions, industries, etc.; and developing and evaluating specific, promising strategies. Much of the thinking on relevant channels and promising strategies was discussed only briefly, and left to future research. However, for strategy we might keep in mind enthusiastic versions of current market transformation initiatives, government procurement programs, and demonstration programs.

In reality, this thesis raises more questions than it answers at every stage. We have arrived at a reasonable understanding of the diffusion of design-based, configurational energy efficiency technology, but what of the vast set of other efficiency technologies? We understand the degree to which NAECA is technology-forcing, but what of the other types of regulations that affect building energy efficiency? We understand the dimensions of the problem in framing a technology-based strategy to improve energy efficiency, but how can this aggressive approach be reconciled with likely industry opposition? How do we rally public interest around an issue which is uninteresting at the level of the individual decision-maker, but so important at an aggregate level? How can public institutions shape the pattern of technological change and technology adoption? Such questions are only raised, not answered, by this thesis. At minimum, the thesis frames a technologically proactive approach to understanding and improving residential energy efficiency.